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A RAND NOTE

Aircraft Airframe Cost Estimating Relationships: Fighters

R. W. Hess, H. P. Romanoff

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This Note is part of a series of Notes that derive a set of equations suitable for estimating the acquisition costs of various types of aircraft airframes in the absence of detailed design and manufacturing information. A single set of equations was selected as being the most representative and applicable to the widest range of estimating situations. For fighters, the the equation set uses airframe unit weight as the variable. Keywords:

PREFACE

This Note describes the derivation of a set of equations suitable for estimating the acquisition costs of fighter aircraft airframes in the absence of detailed design and manufacturing information. In broad form, the research represents an extension of the results published in J. P. Large et al., *Parametric Equations for Estimating Aircraft Airframe Costs*, R-1693-1-PA&E, The RAND Corporation, February 1976, and used in the RAND aircraft cost model, DAPCA: H. E. Boren, Jr., *A Computer Model for Estimating Development and Procurement Costs of Aircraft (DAPCA-III)*, R-1854-PR, The RAND Corporation, March 1976.

The present effort was undertaken in the context of a larger overall study whose objectives included: (a) an analysis of the utility of dividing the full estimating sample into subsamples representing major differences in aircraft type (attack, fighter, and bomber/transport); and (b) an examination of the explanatory power of variables describing program structure and airframe construction techniques. Additionally, for the fighter subsample only, the study investigated the possible benefits of incorporating an objective technology measure into the equations. A detailed description of the overall study, including the research approach, evaluation criteria, and database may be found in R. W. Hess and H. P. Romanoff, *Aircraft Airframe Cost Estimating Relationships: Study Approach and Conclusions*, R-3255-AF, The RAND Corporation, December 1987.

To address the issue of sample homogeneity, each of the subsamples, as well as the full sample, had to be investigated in detail with the ultimate goal of developing representative sets of cost estimating relationships (CERs) for each. The purpose of this Note is, therefore, to document the selection of a representative set of CERs for the fighter subsample. Study results concerning the full estimating sample as well as the other subsamples are available in a series of companion Notes:

Aircraft Airframe Cost Estimating Relationships: All Mission Types, N-2283/1-AF, December 1987.

Aircraft Airframe Cost Estimating Re..tionships: Bombers and Transports, N-2283/3-AF, December 1987.

Aircraft Airframe Cost Estimating Relationships: Attack Aircraft, N-2283/4-AF, December 1987.

This research was undertaken as part of the Project Air Force study titled "Cost Analysis Methods for Air Force Systems," which has been superseded by "Air Force Resource and Management Issues in the 1980s" in the Resource Management Program.

While this report was in preparation, Lieutenant Colonel H. P. Romanoff, USAF, was on duty in the System Sciences Department of The RAND Corporation. At present, he is with the Directorate of Advanced Programs in the Office of the Assistant Secretary of the Air Force for Acquisition.

SUMMARY

This Note presents generalized equations for estimating the development and production costs of fighter aircraft airframes. It provides separate estimating relationships, in the form of exponential equations, for engineering, tooling, manufacturing labor, manufacturing material, development support, flight test, and quality control as well as for total program cost. The estimating relationships have been derived from a database consisting of 17 fighters with first flight dates ranging from 1948 to 1978. The aircraft technical data were obtained for the most part from either original engineering documents such as manufacturer's performance substantiation reports or from official Air Force and Navy documents. The cost data were obtained from the airframe manufacturers either directly from their records or indirectly through standard Department of Defense reports such as the Contractor Cost Data Reporting System.

For each airframe cost category there are generally several potentially useful estimating equations. Nevertheless, a single set of equations has been selected as being, in our judgment, the most representative and applicable to the widest range of estimating situations. The selection rationale, as well as the alternative equations and supporting data, are presented in this Note so that interested readers may make their own judgments.

The recommended equation set uses only one variable--airframe unit weight--and is based on a subsample consisting of six post-1960 fighters. This equation set, which was visually fit to the data, provides results that we believe to be more credible than those produced by multiple least-squares regression analysis of the full 17 aircraft fighter sample.

With the exception of a variable that distinguishes the older fighters (which were essentially gun platforms) from the more modern fighters with sophisticated fire control and missile armament, our attempts to incorporate construction and program characteristics were

not successful. Although variables characterizing the equipment placed within the airframe structure were frequently found to be statistically significant, they did not, as a rule, result in any substantial improvement in the quality of the equations. In most cases, the equations incorporating such variables did not produce results that we viewed as credible. Moreover, even in those few instances where the equations did produce credible results, the reduction in the standard error of estimate was never more than two or three percentage points.

A comparison of the recommended fighter equation set with the all-mission sample equation set (developed in N-2283/1-AF) was also undertaken. In terms of the estimates obtained from each set for the F-4, F-111, F-14, F-15, F-16, and F-18, we found that the fighter equation set will produce larger estimates than the all-mission type equation set for relatively light, "slow" fighters (e.g., the F-16 and F-18) and smaller estimates for relatively heavy, fast fighters (e.g., the F-4, F-111, F-14, and F-15). However, using the average absolute relative derivations of the six post-1960 fighters as a basis, we found that the fighter equation set was only slightly more accurate than the all-mission type set despite the focused nature of the fighter database.

The ultimate test will, of course, be the set's ability to estimate the cost of future fighters. Unfortunately (from an estimating point of view), airframes are changing dramatically with respect to materials (e.g., more extensive use of composites), design concepts (e.g., concepts to increase fuel efficiency and to reduce radar cross-section), and manufacturing techniques (e.g., use of computers and robots). We believe that the material and design changes will act to increase unit costs but we are uncertain about the net impact of capital equipment changes. In any case, it is highly unlikely that any of the equation sets presented in this document will overestimate the costs of future fighters.

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FIGURES

TABLES

MNEMONICS

AUW	Airframe unit weight (lb)
AVAUW	Ratio of avionics weight to airframe unit weight
BLBOX	Number of black boxes
BREG	Breguet range factor (n.mi.)
CA	Cumulative average
CARRDV	Carrier capability designator (1 = no; 2 = yes)
CLIMB	Rate of climb (ft/min)
DS	Development support cost (thousands of 1977 dollars)
ENERGY	Maximum specific energy (ft)
$ENGR_{100}$	Cumulative engineering hours for 100 aircraft (thousands)
ENGDV	New engine designator (1 = no; 2 = yes)
ENGLOC	Engine location designator (1 = embedded in fuselage; 2 = in nacelles under wing)
EXPDV	Contractor experience designator (1 = no; 2 = yes)
EW	Empty weight (lb)
EWAUW	Ratio of empty weight less airframe unit weight to airframe unit weight
FT	Flight test cost (thousands of 1977 dollars)
$LABR_{100}$	Cumulative manufacturing labor hours for 100 aircraft (thousands)
$MATL_{100}$	Cumulative manufacturing material cost for 100 aircraft (thousands of 1977 dollars)
PFFD	Predicted first flight date (months since January 1, 1940)

PRGDV	Program type designator (1 = concurrent; 2 = prototype)
$PROG_{100}$	Cumulative program cost for 100 aircraft (thousands of 1977 dollars)
Q	Quantity
iQC_{100}	Cumulative quality control hours for 100 aircraft (thousands)
SP	Maximum speed (kn)
SPCLS	Speed class (1 = less than Mach .95; 2 = Mach .95 to 1.94; 3 = Mach 1.95 to Mach 2.5; 4 = greater than Mach 2.5)
SPPWR	Specific power (hp/lb)
STREFF	Structural efficiency factor
SUSLD	Maximum sustained load factor (g's)
TESTAC	Number of test aircraft
THWT	Thrust-to-weight ratio
$TOOL_{100}$	Cumulative tooling hours for 100 aircraft (thousands)
TOOLCP	Maximum tooling capability (aircraft per month)
USELD	Useful load fraction
ULTLD	Design ultimate load factor (g's)
WTAREA	Wetted area (sq ft)
WGTYPE	Wing type (1 = straight; 2 = swept; 3 = delta; 4 = variable sweep)
WGWET	Ratio of wing area to wetted area
WSDV	Weapon system designator (1 = no; 2 = yes)

EVALUATION CRITERIA NOTATION

Notation	Explanation
EQ SIG: F-TEST	Equation as a whole is not significant at 5% level (based on F-statistic)
EXP MAG: variable mnemonic	Question exists regarding magnitude of variable exponent (reasonableness)
EXP SIGN: variable mnemonic	Sign of variable exponent does not agree with a priori notions
F	F-statistic
IO: aircraft identification	Based on "Cook's Distance," aircraft is indicated to be influential observation
LDIFF: variable mnemonic	Limited differentiation in dummy variable; coefficient determined by single observation or portion of dummy variable range not included in a subsample
MCOL: r(variable) > .7, .8, or .9	Indicates degree of intercorrelation of specified variable with other equation variables (only provided when threshold of .7 is exceeded)
N	Number of observations
R^2	Coefficient of determination
RP: CUR: OVER/UNDER	Residual pattern indicates that the most recently developed aircraft in the sample are over or underestimated
RP: DIST	Residual pattern indicates that the error is not normally distributed with zero mean and constant variance
SEE	Standard error of estimate
VAR SIG: variable mnemonic	Variable is not significant at the 5% level (t-statistic)[1]

[1]Variable significance is provided in parentheses beneath each variable.

I. INTRODUCTION

Parametric models for estimating aircraft airframe acquisition costs have been used extensively in advanced planning studies and contractor proposal validation. These models are designed to be used when little is known about an aircraft design or when a readily applied validity and consistency check of detailed cost estimates[1] is necessary. They require inputs that: (a) will provide results that are relatively accurate; (b) are logically related to cost; and (c) can easily be projected prior to actual design and development. The intent is to generate estimates that include the cost of program delays, engineering changes, data requirements, and phenomena of all kinds that occur in a normal aircraft program.

Since 1966, RAND has developed three parametric airframe cost models.[2] These models have been characterized by: (a) easily obtainable size and performance inputs (weight and speed); (b) the estimation of costs at the total airframe level; and (c) the utilization of heterogeneous aircraft samples. They have normally been updated when a sufficient number of additional aircraft data points has become available to suggest possible changes in the equations. Such is the case with the present effort: the A-10, F-15, F-16, F-18, F-101, and S-3 aircraft have been added to the full estimating sample.[3]

In addition to the expansion of the database, we also examined: (a) the utility of dividing the estimating sample into subsamples representing major differences in aircraft type (attack, fighter, bomber/transport); (b) the explanatory power of variables describing

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[1]Examples of this latter application include the Independent Cost Analysis (ICA) prepared as part of the Defense Systems Acquisition Review Council (DSARC) process and government analyses of contractor cost proposals during source selections.

[2]See Refs. 1, 2, and 3.

[3]Additionally, the F-86, F-89, and F3D, which were dropped from the DAPCA-III estimating sample, were reintroduced.

program structure and airframe construction techniques; and (c) the possible benefits of incorporating an objective technology measure into the fighter sample equations. In order to address the issue of sample homogeneity, each of the subsamples, as well as the full sample, had to be investigated in detail with the ultimate goal of developing representative sets[4] of cost estimating relationships (CERs) for each. The purpose of this Note is, therefore, to document the selection of a representative set of CERs for the fighter subsample.

A detailed description of the overall study, including the research approach, evaluation criteria, and database, may be found in the companion Report, R-3255-AF, *Aircraft Airframe Cost Estimating Relationships: Study Approach and Conclusions.*

APPROACH AND PRINCIPAL RESULTS

Our analysis examined a large number of potentially useful equations for each of the airframe cost elements. In fact, this report contains each of the 231 equations that met our initial screening criterion relative to variable significance (discussed in Section II). Additionally, data plots have been included for each cost element. Presenting such a large number of equations and supporting data serves two purposes. First, the information contained in the equations and plots can provide an improved understanding of the factors that influence airframe costs. Thus, the estimator will have a more complete context in which to judge the applicability of specific estimating equations. Second, we are offering the user alternatives for each cost element that may be better suited in a particular case than any single equation that we might have selected if we chose to document just one. This is important since, in general, the study did not produce one equation for each cost element that is clearly preferred over all others. The user should review all of the results before selecting the equations to be used in a particular situation.

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[4]A set encompasses the following cost elements: engineering, tooling, manufacturing labor, manufacturing material, development support, flight test, and quality control.

The basic estimating sample used in our analysis consists of fifteen "new design" fighter aircraft with first flight dates ranging from 1948 to 1972: F3D, F3H, F4D, F-4, F-14, F-15, F-86, F-89, F-100, F-101, F-102, F-104, F-105, F-106, and F-111.[5] All technical data were obtained from either original engineering documents or from official Air Force or Navy aircraft characteristics summaries.

Our analysis of the *basic* 15-aircraft estimating sample led to the derivation of what we felt to be a reasonably representative set of CERs. The estimating relationships, which were visually fit to the data, were based on a subsample of the *basic* sample consisting only of those fighters with post-1960 first flight dates (the F-4, F-111, F-14, and F-15). The decision to use the more limited group of fighters was the result of observations made during the course of the study that raised questions concerning the applicability of some of the older fighters in the sample to fighters of the future. We concluded that the more limited post-1960 experience would be a better guide to the future.

Subsequent to the completion of the analysis of the *basic* sample, but prior to the publication of this Note, however, cost data for the F-16 and F-18 became available. Consequently, we reexamined the cost scattergrams (updated to include the F-16 and F-18) to see whether any changes in the visually fit equations were suggested. As a result of this reexamination, we made relatively minor modifications to two of the estimating relationships (labor and material). The final recommended set of fighter airframe CERs, which incorporates these modifications, is provided in Table 1. The fighters that served as the basis for the equations have characteristic values that span the ranges shown below.

Characteristic	Post-1960 Database Range
Airframe unit weight (lb)	9,565 - 33,150
Empty weight (lb)	14,062 - 46,170
Speed (knots)	1,000+ - 1,250+
Number of flight test aircraft	7 - 20

[5]The F-16 and F-18 were not a part of the *basic* estimating sample but, as will be explained subsequently, were incorporated into our analysis prior to the publication of this Note.

Table 1

RECOMMENDED SET OF FIGHTER AIRFRAME CERs
(Based on post-1960 fighters)

$$ENGR_{100} = 2.31\ AUW^{.887}$$

$$TOOL_{100} = 1.38\ AUW^{.883}$$

$$LABR_{100} = 25.4\ AUW^{.678}$$

$$MATL_{100} = 43.3\ AUW^{.878}$$

$$DS = .75 * ENGRC_{1}$$

$$FT = 27100\ TESTAC^{.687}$$

$$QC = .142 * LABR_{100}$$

$$PROG_{100} = 550\ AUW^{.812}$$

AUW	= airframe unit weight (lbs)
DS	= development support cost (thousands of 1977 dollars)
$ENGR_{100}$	= cumulative engineering hours for 100 aircraft (thousands)
$ENGRC_{1}$	= nonrecurring engineering cost (thousands of 1977 dollars)(a)
FT	= flight test cost (thousands of 1977 dollars)
$LABR_{100}$	= cumulative manufacturing labor hours for 100 aircraft (thousands)
$MATL_{100}$	= cumulative manufacturing material dollars for 100 aircraft (thousands of 1977 dollars)
QC_{100}	= cumulative quality control hours for 100 aircraft (thousands)
$PROG_{100}$	= cumulative total program cost for 100 aircraft (thousands of 1977 dollars)
TESTAC	= number of flight test aircraft
$TOOL_{100}$	= cumulative tooling hours for 100 aircraft (thousands)

(a)$ENGRC_{1} = \$27.50 * ENGR_{100} * 100^{-.164}$ where the factor $100^{-.164}$ is used to adjust cumulative engineering hours from a quantity of 100 to a quantity of 1 (assuming a 112% cumulative total slope) and where \$27.50 represents the fully burdened engineering hourly labor rate in 1977 dollars.

In order to adjust the quantity-dependent estimating relationships to quantities other than 100,[6] the following slopes are recommended:

	Cumulative Total Slope (%)	Cumulative Total Exponent
Engineering	112	.163
Tooling	120	.263
Manufacturing labor	158	.660
Manufacturing material	166	.231
Quality control	164	.714
Total program cost	128	.356

The manufacturing material, development support, flight test, and total program cost categories are all estimated directly in 1977 dollars. In order to convert the remaining cost categories that are estimated in manhours to 1977 dollars, the following fully burdened hourly labor rates are suggested:

Engineering	27.50
Tooling	25.50
Manufacturing labor	23.50
Quality control	24.00

For estimates in 1986 dollars, the following hourly labor rates and adjustment factors are suggested:

Engineering	59.10
Tooling	60.70
Manufacturing labor	50.10
Quality control	55.40
Manufacturing material (index)	1.94
Development support (index)	1.94
Flight test (index)	1.94
Total program cost (index)	2.13

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[6] $\text{Cost}(Q_{new}) = \text{Cost}(100) * (Q_{new}/100)^{\text{exponent}}$

NOTE ORGANIZATION

Section II provides brief descriptions of the database and statistical analysis methods. Section III provides an initial overview of the individual cost element analyses that follow. Sections IV through XI provide--by cost element--data plots, estimating relationships meeting our initial screening criterion, and the rationale for selection of "representative" equations.[7] Section XII explains the selection of the recommended equation set. Section XIII details the incorporation of the F-16 and F-18 data. Finally, Sec. XIV summarizes the main findings of the analysis.

Two appendixes contain miscellaneous supporting information. Appendix A contains correlation matrices. Appendix B contains calculated costs for several equation sets for the F-4, F-111, F-14, and F-15.

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[7]As stated previously, the detailed analysis was not repeated when the F-16/F-18 data were obtained. Therefore, Secs. II-XII are based on the 15-aircraft estimating sample, which does *not* include the two most recent fighters.

II. DATABASE AND ANALYTICAL APPROACH

As stated previously, a detailed description of the research approach, evaluation criteria, and database for this study may be found in R-3255-AF. However, in order that this Note may have a degree of self-sufficiency, a synopsis of the database and analytical approach is presented prior to the reporting of results.

ESTIMATING SAMPLE

The cost data used in this study have been obtained from both government and industry sources. The "basic" fighter sample consists of the following 15 "new design" aircraft:[1]

Model	First Flight Date[2]
F-86	1948
F3D	1950
F-89	1950
F-100	1953
F4D	1954
F-101	1954
F3H	1955
F-102	1955
F-104	1956
F-105	1956
F-106	1956
F-4	1961
F-111	1967
F-14	1970
F-15	1972

[1]The classification of an aircraft as new or derivative is not an entirely objective procedure. For example, although the F-102A program laid the groundwork for the F-106A, the F-106A is classified as a new design in the database because, in contrast to the F-102A, it had a new engine, relocated air intakes, variable geometry air inlets, a modified vertical stabilizer and markedly better performance. (Ref. 4, p. 14.)

[2]The first flight dates presented in this report are intended to reflect the first flight date of the version of the aircraft that was most representative of the aircraft that was to become operational. Put another way, these dates are intended to reflect the first flight date of the developmental aircraft and not earlier experimental or prototype aircraft. Thus, although the F-4A aircraft first flew in May 1958, the first flight date of the F-4B aircraft is presented.

DEPENDENT VARIABLES

Costs have been dealt with at both the total program level[3] and at the major cost element level (engineering, tooling, manufacturing labor, manufacturing material, development support, flight test, and quality control).[4] The relative importance of various cost categories is shown in Table 2 for four alternative production quantities. Other things being equal, the analyst would obviously hope that the estimating relationship for manufacturing labor was the most accurate because of its relatively large contribution to program cost.

Engineering, tooling, manufacturing labor, and quality control are estimated in terms of manhours rather than dollars for two reasons: (a) it avoids the need to make adjustments for annual price changes, and (b) it permits comparison of real differences in labor requirements.[5] Manufacturing material, development support, and flight test do not lend themselves to this approach and were therefore estimated in terms of dollars (in this case, constant 1977 dollars).

Table 2

PERCENTAGE BREAKDOWN OF FIGHTER AIRFRAME PROGRAM COSTS
(15-Aircraft Average Costs)

	Quantity			
Cost Element	25	50	100	200
Engineering	25	23	20	17
Tooling	16	16	15	14
Manufacturing labor	22	27	32	36
Manufacturing material	8	10	13	17
Development support	13	10	8	5
Flight test	14	11	8	6
Quality control	2	3	4	5
	100%	100%	100%	100%

[3] Total program costs are "normalized" values and not the actual reported dollar amounts. They are normalized in the sense that the dollar amounts for engineering, tooling, manufacturing labor, and quality control have been determined by applying fully burdened, industry-average labor rates to the hours reported for each category.

[4] Cost element definitions are provided in Appendix A of R-3255-AF.

[5] The major limitation of the manhour approach is that it does not account for differences in overhead rates. Consequently, differences in such things as capital/labor ratios cannot be addressed.

POTENTIAL EXPLANATORY VARIABLES

In order to have been included among the characteristics that were considered for inclusion in the CERs, the following requirements must have been fulfilled:

1. The variable had to be logically related to cost: that is, a rationale had to be constructed that would explain why cost should be influenced by the variable.

2. The variable had to be one that was "readily available" in the early stages of aircraft conceptualization.

3. The variable had to have an *available* historical record.

During the formulation stage of this study, 28 aircraft characteristics were identified as potential explanatory variables for the fighter sample CERs. Values for these characteristics, which are grouped into four general categories[6]--size, performance, construction, and program--are provided in Table 3. As indicated, the only variable whose minimum and maximum values span a range of over an order of magnitude is climb rate. Additionally, there is no variation in the engine location designator--all fighters have engines mounted in the fuselage.

There are, of course, differences that are not accounted for in Table 3 between the aircraft. Some of the differences between the aircraft relate to the way an aircraft is constructed (materials, manufacturing technology), others to the way the program is managed. In any case, it is difficult to find an aircraft without at least one unique aspect. Therefore, the following list is intended only to be indicative of the types of differences that are difficult to account for in a generalized parametric model.

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[6]The fighter technology index is elaborated upon in the following subsection.

Table 3

AIRCRAFT CHARACTERISTIC VALUES

	Size			Technical/Performance							
Aircraft	Airframe Unit Weight	Empty Weight	Wetted Area	Maximum Speed	Speed Class	Specific Power	Maximum Specific Energy	Climb Rate	Maximum Sustained Load Factor	Thrust to Weight Ratio	Breguet Range Factor
F3D	10,136	14,860	1,843	470	1	.40	47,700	4,100	.90	.275	3750
F3H	13,898	21,270	1,908	622	1	.89	58,700	13,000	3.00	.466	4480
F4D	8,737	16,050	1,500	628	1	1.41	64,500	20,200	3.50	.731	3820
F-4	17,220	27,530	2,150	1222	3	2.62	110,000	40,600	2.90	.700	4200
F-14	26,500	36,825	3,155	*	*	*	*	*	*	*	*
F-15	17,550	26,795	2,646	*	*	*	*	*	*	*	*
F-86	6,788	10,040	1,070	590	1	.67	59,500	7,650	2.90	.367	4870
F-89	18,119	23,870	-	546	1	.67	-	11,800	2.40	.400	3970
F-100	12,118	18,260	1,509	752	2	1.40	64,400	25,700	3.20	.607	4920
F-101	13,423	24,720	2,060	872	2	1.80	77,700	29,600	2.50	.671	4530
F-102	12,304	19,460	2,170	680	2	1.19	65,700	18,700	3.00	.571	5390
F-104	7,963	11,570	1,078	1150	3	2.48	117,000	51,500	2.70	.703	4500
F-105	19,301	24,500	1,998	1112	3	2.00	93,000	38,300	2.50	.585	5200
F-106	14,620	23,180	2,230	1153	3	2.18	99,000	34,500	3.20	.616	5400
F-111	33,150	46,170	2,580	1262	3	1.94	126,000	12,600	2.00	.501	6450
Mean	15,455	23,007	1,993	913		1.78	89,393	27,850	2.86	.596	4893
Standard Deviation	7,058	9,335	584	314		1.02	30,821	17,508	0.77	.189	857

*Classified.
-Not available.

Table 3 (continued)

	Technical/Performance		Construction						
Aircraft	Useful Load Fraction	Predicted First Flight Date	Design Ultimate Load Factor	Structural Efficiency Factor	Carrier Capability Designator	Engine Location Designator	Wing Type	Ratio of Wing Area to Wetted Area	Ratio of (EW-AUW) to AUW
F3D	.484	109	9.00	.0459	2	1	1	.218	.47
F3H	.455	174	11.25	.0372	2	1	2	.272	.53
F4D	.427	167	9.50	.0433	2	1	3	.371	.84
F-4	.508	244	12.75	.0291	2	1	2	.247	.60
F-14	*	355	*	*	2	1	4	.179	.39
F-15	.499	432	11.00	.0321	1	1	2	.230	.53
F-86	.416	142	11.00	.0328	1	1	2	.269	.48
F-89	.347	108	8.50	.0469	1	1	1	-	.32
F-100	.371	164	11.00	.0368	1	1	2	.255	.51
F-101	.493	180	11.00	.0240	1	1	2	.179	.84
F-102	.374	171	10.50	.0333	1	1	3	.305	.58
F-104	.508	217	11.00	.0335	1	1	2	.182	.45
F-105	.538	216	13.00	.0383	1	1	2	.193	.27
F-106	.363	209	10.50	.0326	1	1	3	.312	.59
F-111	.533	267	11.00	.0340	1	1	4	.203	.39
Mean	.453	210	10.72	.0362				.244	.52
Standard Deviation	.065	88	1.17	.0063				.058	.16

*Classified.
-Not available.

Table 3 (continued)

Aircraft	Construction		Program					
	Ratio of Avionics Wt to AUW	Number of Black Boxes	Number of Test Aircraft	Maximum Tooling Capability	New Engine Designator	Contractor Experience Designator	Weapon System Designator	Program Type Designator
F3D	.145	9	13	20	1	2	1	2
F3H	.060	6	18	13	2	1	1	2
F4D	.215	9	13	20	2	1	1	2
F-4	.101	14	7	15	1	1	2	1
F-14	.112	21	12	8	1	1	2	1
F-15	.090	24	20	12	2	1	2	1
F-86	.106	4	12	30	2	1	1	2
F-89	-	9	6	25	1	2	1	2
F-100	.016	5	13	50	1	1	1	2
F-101	.075	9	17	20	1	1	1	1
F-102	.164	9	31	45	1	2	2	1
F-104	.076	6	19	20	2	1	1	2
F-105	.074	11	15	17	2	1	2	1
F-106	.190	11	26	20	1	1	2	1
F-111	.081	18	18	21	2	2	2	1
Mean	.108	11	16	19				
Standard Deviation	.054	6	7	10				

*Classified.
-Not available.

- The F-86 was the first swept wing aircraft.
- The F-100 was the first aircraft capable of sustained supersonic flight.
- The F4D was the first operational delta wing aircraft.
- The F-102 did not meet its speed performance specifications until after a major redesign.
- The F-104 was the first operational Mach 2+ aircraft.
- The F-106 was a design outgrowth of the F-102.
- The F-4 design evolved (during the original development phase) from a single-seat, attack aircraft with four 20-mm cannons to a high-altitude interceptor with two crew positions and missile armament.
- The F-111 was the first aircraft for which common Air Force/Navy usage was made a requirement at inception.

A priori notions regarding the effect an increase in the value of an explanatory variable might have on each of the cost elements are indicated in Table 4. A plus indicates a positive effect; a minus a negative effect. An effect that was thought to be negligible is indicated by a blank while an uncertain effect is indicated by a question mark.

TECHNOLOGY INDEX

Recent RAND work[7] has resulted in the development of an expression that relates the time of appearance of an aircraft design to its level of performance, which is interpreted as a measure of its level of technological sophistication.[8] The expression--which includes specific power, the Breguet range factor, sustained load factor, fuel fraction, and a carrier-capability designator--is represented in Fig. 1.

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[7]See Ref. 4.

[8]It should be noted that in addition to the technology index itself, another benefit of the technology study to this analysis was the identification of several individual explanatory variables that had not previously been tested for significance in airframe cost equations.

Table 4

A PRIORI NOTIONS REGARDING EFFECT OF INCREASE IN EXPLANATORY VARIABLE ON COST ELEMENT

Explanatory Variable	Engr	Tooling	Mfg Labor	Mfg Matl	Dev Support	Flight Test	Quality Control	Total Program
Size								
Airframe unit weight (AUW)	+	+	+	+	+	+	+	+
Empty weight (EW)	+	+	+	+	+	+	+	+
Wetted area	+	+	+	+	+	+	+	+
Technical/Performance								
Maximum speed[a]	+	+	+	+	+	+	+	+
Speed class	+	+	+	+	+	+	+	+
Specific power	+	+	+	+	+	+	+	+
Maximum specific energy	+	+	+	+	+	+	+	+
Climb rate	+	+	+	+	+	+	+	+
Maximum sustained load factor	+	+	+	+	+	+	+	+
Thrust-to-weight ratio	+	+	+	+	+	+	+	+
Breguet range factor	+	+	+	+				+
Useful load fraction	+	+	+	+				+
Predicted first flight date (technology index)	+		–[h]	+	+	+		+
Predicted first flight date (composite performance)	+	+	+	+	+	+	+	+
Construction								
Design ultimate load factor	+		+	+	+			+
Structural efficiency factor[b]	–		–	–	–			–
Carrier capability designator[c]	+		+	+	+	+		+
Engine location designator[d]	–	?	–	+				?
Wing type designator[e]	+	+	+		+	+		+
Ratio of wing area to wetted area		–	–					–
Ratio of (EW-AUW)/AUW	+		+	+	+	+	+	+
Ratio of avionics weight to AUW	+		+	+	+	+	+	+
Number of black boxes	+		+	+	+	+	+	+
Program								
Number of test aircraft						+		
Maximum tooling capability		+	–					?
New engine designator[c]	+					+		+
Contractor experience designator[f]	+	+	+	+	+	+	+	+
Weapon system designator[c]	+	+	+	+	+	+	+	+
Program type designator[g]	?[i]	?[i]			?[i]	?[i]		?[i]

[a] Speed class: 1 = less than Mach .95; 2 = Mach .95 to Mach 1.94; 3 = Mach 1.95 to Mach 2.5; 4 = greater than Mach 2.5.

[b] Low values are more difficult to achieve.

[c] No = 1/Yes = 2.

[d] Engine location: embedded in fuselage = 1; in nacelles under wing = 2.

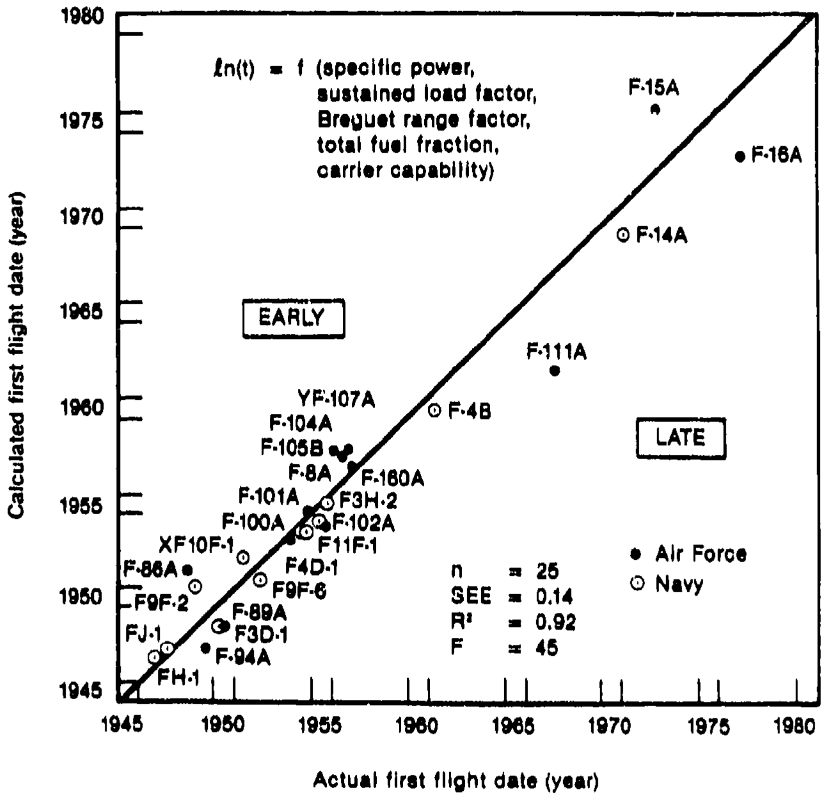
[e] Wing types: 1 = straight; 2 = swept; 3 = delta; 4 = variable sweep.

[f] Yes = 1/No = 2.

[g] Concurrent = 1/Prototype = 2.

[h] Over time, major assembly labor hours have tended to decrease because of improvements in manufacturing methods (e.g., unitized design) while fabrication labor hours have tended to increase because of introduction of titanium and composite materials. The net effect has been a decrease in manufacturing hours.

[i] Not known whether total cost (prototype effort plus full-scale development) for prototype program is greater or less than for concurrent program.



$$\ln(t) = 3.530 + .059\left[\frac{\text{Thrust} - V_{max}}{100W_{cbt}}\right] + 1.768\left[\frac{\text{Breguet range factor}}{10{,}000}\right] + 1.186\left[\frac{\text{Sustained load factor}}{10}\right]$$

$$+ .526\left[\begin{matrix}\text{Total}\\ \text{fuel}\\ \text{fraction}\end{matrix}\right] - .168\left[\begin{matrix}\text{Carrier}\\ \text{capability}\end{matrix}\right]$$

NOTE: t = calculated first flight date measured in months since January 1, 1940. Thrust measured in pounds, V_{max} in knots, combat weight in pounds. Carrier capability variable: 1 denotes no capability, 0 denotes capability.

Fig. 1—Multivariate technology trend for new fighter designs

The vertical axis measures the first flight date calculated by inserting aircraft performance parameters in the technology equation and the horizontal axis measures the actual first flight date for each aircraft. The distribution of the 25 data points about the 45 degree line provides one measure of how well the equation fits the data sample. Points plotted above the 45 degree line represent aircraft that flew earlier than the date predicted by the equation, and the converse holds for points plotted below the line. The magnitude and sign of the residual of the technology equation determine where a particular aircraft point falls relative to the 45 degree trend line, with the residual representing all the unquantifiable factors that influence when the first flight of an aircraft occurs, including technological factors not covered by the independent variable parameter set, scheduling decisions, Congressional and service funding decisions, development philosophy, etc. Accordingly, one should interpret the results from the equation only as a gross indication of average technological trends in fighter aircraft development, remembering that other factors can also influence the time at which a particular level of technology becomes available.[9]

APPROACH

Potential explanatory variables have been divided into four general categories--size, performance, construction, and program (see Table 4). As discussed in R-3255-AF, the "ideal" airframe cost-estimating relationship would incorporate one explanatory variable from each category. Thus, there would be four independent variables per estimating relationship. For the basic all-mission type estimating sample, which has 32 observations, the possible incorporation of four independent variables presents no difficulties since there would still be 27 degrees of freedom left with which to estimate the error term. Unfortunately, the basic fighter subsample has only 15 observations and the incorporation of four explanatory variables would leave only 10 degrees of freedom with which to estimate the error term. This is less than half the comparable value for the full estimating sample. Consequently, it is our judgment that the potential number of independent variables per equation should be limited to a value less

[9]See Ref. 4, p. 27.

than 4. On the other hand, the bomber/transport and attack aircraft subsamples, which have only eight and seven observations, respectively, are limited to two variables per equation. Therefore, in order to stay between the two extremes, the number of explanatory variables considered per equation for the fighter sample was tentatively limited to three.[10]

With respect to the specific combinations of variable categories to be examined, it is our understanding that all airframe manufacturers use some measure of size (usually weight) as their basic scaling dimension in developing cost estimates (although other factors frequently do enter in). Consequently, it does not seem unreasonable for a similar assumption to be made on our part--a size variable must appear in all equations (except for flight test in which case the number of test aircraft was the mandatory variable). Therefore, with this additional restriction, the specific variable combinations to be examined for the total sample are as follows:

Size
Size/performance
Size/construction
Size/program
Size/performance/construction
Size/performance/program
Size/performance/technology index

An additional complication arose from the fact that we were not developing a single CER but rather a *set* of CERs. Normally, the development of a representative set of CERS would require the selection of the "best" equation for each cost element. However, past experience indicates that in so doing the resulting equation set would contain different size and performance variables (e.g., airframe unit weight/speed and empty weight/climb rate). Such a result would put the analyst in the unenviable position of trying to explain why a given size/performance variable combination predicts cost more accurately for

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[10]We do not mean to suggest that this limit is an "absolute" maximum for it is not (theoretically, one could use 13 explanatory variables for a fighter equation and still have one degree of freedom left). It simply reflects our *judgment* regarding an appropriate balance between sample size and the potential number of explanatory variables.

one cost element while another size/performance variable combination predicts cost more accurately for another cost element. Furthermore, because of variable interaction (e.g., such as between speed and rate of climb), the user's input task would become more difficult. On the other hand, there is nothing to say that such mixing of the size and performance variables could not in fact be the preferred solution. Consequently, two types of equation sets were developed: one that maintains the integrity of the set size and performance variables and one that utilizes the "best" equation for each cost element regardless of the size or performance variables.

The first step in developing a representative set of CERs was to identify all potentially useful estimating relationships for each cost element resulting from the variable combinations listed above. For this first step, "potentially useful" included only those estimating relationships in which all equation variables were significant at the 5 percent level. For the one- and two-variable combinations, all possible equations were examined. An initial inspection was next undertaken in order to identify the "most promising" of the size/performance combinations. Then, for the three-variable combinations, each of the construction and program variables was examined in conjunction with the "most promising" of the size/performance variable combinations.

Each equation satisfying the initial screening criterion (5 percent variable significance) was then scrutinized in accordance with a set of evaluation criteria dealing with statistical quality and reasonableness of results (these are described in a subsequent subsection).

The next step was to develop the two types of alternative equation sets discussed previously. For the first type, this consisted of selecting the "best" estimating relationship for each of the "most promising" size/performance combinations for each cost element. For the second type, it consisted of selecting the single "best" estimating relationship for each cost element. Generally speaking, we tried to select estimating relationships that satisfied the following conditions:

- each variable significant at the 5 percent level
- variables taken collectively significant at the 5 percent level
- produce credible results
- free of unusual residual patterns

Once these conditions were satisfied, the objective was minimization of the standard error of estimate. Traditionally, cost analysts have *tried* to achieve a standard error of estimate of + or -20 percent or better. For logarithmic models, this is approximately equivalent to 0.18 (-16 percent, +20 percent).

The final step was the selection of a "most" representative set. This final selection was done primarily on the basis of a comparison of the individual equation standard errors of estimate and by how well (in terms of relative deviation) the sets as a whole estimated the costs of a subsample of four recent aircraft.

Multiple regression analysis was used to examine the relationship between cost and the explanatory variables. Because of time restrictions, only one equation form was investigated--logarithmic-linear. The linear model was rejected because its main analytic property--constant returns to scale--does not correspond to real world expectations. Of the two remaining equation forms considered (logarithmic and exponential), the logarithmic model seemed most appropriate for the cost-estimation process since it minimizes relative errors rather than actual errors as in the exponential model.

Cost element categories that are a function of quantity were examined at a quantity of 100. Developing the estimating relationships at a given quantity rather than utilizing quantity as an independent variable in the regression analysis avoids the problem of unequal representation of aircraft (caused by unequal numbers of lots).

EVALUATION CRITERIA

The estimating relationships obtained in this analysis were evaluated on the basis of their statistical quality, intuitive reasonableness, and predictive properties.

Statistical Quality

Variable Significance. Variable significance was utilized as an initial screening device to reduce the number of estimating relationships requiring closer scrutiny. Normally, only those equations for which all variables were significant at the 5 percent level (one-sided t-test) were reported in this Note. Occasionally, however, this criterion was relaxed in order that a useful comparison could be provided or so that the requirement concerning the integrity of the set size and performance variables could be examined. When an equation is reported for which not all equation variables are significant at the 5 percent level, it is denoted as follows:

VAR SIG: variable mnemonic

Coefficient of Determination. The coefficient of determination (R^2) was used to indicate the percentage of variation explained by the regression equation.

Standard Error of Estimate. The standard error of estimate (SEE) was used to indicate the degree of variation in the data about the regression equation. It is given in logarithmic form but may be converted into a percentage of the corresponding hour or dollar value by performing the following calculations:

(a) $e^{+SEE}-1$

(b) $e^{+SEE}-1$

For example, a standard error of 0.18 yields standard error percentages of +20 and -16.

F-Statistic. The F-statistic was used to determine collectively whether the explanatory variables being evaluated affect cost. Those equations for which the probability of the null hypothesis pertaining was greater than 0.05 have been identified as follows:

EQ SIG: F-TEST

Generally speaking, equations so identified were not considered for inclusion in a representative equation set.

Multicollinearity. Estimating relationships containing variable combinations with correlations greater than .70 are identified according to the degree of intercorrelation:

MCOL: r(variable mnemonic) > .7, .8, or .9

where the variable identified in parentheses is the equation variable showing the greatest collinearity. Generally speaking, estimating relationships with intercorrelations greater than .8 were avoided when selecting a representative equation set.

Residual Plots. Plots of equation residuals were given cursory examinations for unusual patterns. In particular, plots of residuals versus predictions (log/log) were checked to make sure that the error term was normally distributed with zero mean and constant variance. Additionally, plots of residuals versus time (log/linear) were examined to see whether or not the most recent airframe programs were over- or underestimated. The existence of such patterns resulted in one of the following designations:

RP: DIST (errors not normally distributed)
RP: CUR: OVER or UNDER (most recent aircraft over- or underestimated)

Generally speaking, we *tried* to avoid the use of estimating relationships with patterns in the representative equation sets.

Influential Observations. "Cook's Distance" was utilized to identify influential observations in the least-squares estimates. For this analysis, an influential observation was defined as one that if deleted from the regression, would move the least-squares estimate past the edge of the 10 percent confidence region for the equation coefficients. Such observations are identified as follows:

IO: aircraft identification

When an observation was consistently identified as influential, it was reassessed in terms of its relevance to the sample in question. If a reasonable and uniform justification for its exclusion could be developed, then the observation was deleted from the sample and the regressions rerun (in actuality, this occurred only once--when the B-58 was deleted from the bomber/transport sample). Otherwise, the influential observation was simply flagged to alert the potential user to the fact that its deletion from the regression sample would result in a significant change in the equation coefficients.

Reasonableness

The development of airframe cost-estimating relationships requires variable coefficients that provide both credible results and conform whenever possible to the normal estimating procedures employed by the airframe industry. Such credibility and conformity are reflected in both the signs of the variable coefficients as well as their magnitudes.

Exponent Sign. Estimating relationships for which the sign of the variable coefficient was not consistent with a priori notions (see Table 4) are identified in the following manner:

EXP SIGN: variable mnemonic

Estimating relationships containing such inconsistencies were not considered for inclusion in the representative equation sets.

Exponent Magnitude. Close attention was also paid to the magnitude of variable coefficients. This applied to exponents that were felt to be too small as well as those that were felt to be too large. Estimating relationships containing such variable coefficients are identified as follows:

EXP MAG: variable mnemonic

While determinations of this kind are largely subjective, there was one application that was relatively objective. Traditionally, size variables have always provided returns to scale in the production-oriented cost elements (tooling, labor, material, and total program cost). That is, increases in airframe size are accompanied by less than proportionate increases in cost. If the opposite phenomenon is observed, then it is generally believed to be the result of not adequately controlling for differences in construction, materials, complexity, and/or other miscellaneous production factors. Consequently, equations possessing a size-variable coefficient greater than one were always flagged.

When selecting a representative equation set, we generally tried to avoid estimating relationships containing variables with exponents that we felt were either too large or too small (that is, exponents that placed either too much or too little emphasis on the parameters in question). More restrictively, for the production-oriented cost elements, no estimating relationship possessing a size-variable exponent greater than one was considered for a representative equation set.

Predictive Properties

Confidence in the ability of an equation to accurately estimate the acquisition cost of a future aircraft is in large part dependent on how well the acquisition costs of the most recently produced aircraft are estimated. Normally, statistical quality and predictive capability would be viewed as one and the same. Unfortunately, when dealing with airframe costs this is not always the case because our knowledge of what drives airframe costs is limited and because the sample is relatively small in size and not evenly distributed with respect to first flight date (see Fig. 2). Consequently, the estimating relationships were also evaluated on the basis of how well costs for a subset of the most recent aircraft in the database are estimated.

An indication of an equation's predictive capability would usually be obtained by excluding a few of the most recent aircraft from the regression and then seeing how well (in terms of the relative deviation) the resultant equation estimates the excluded aircraft. However, in this case, the small sample size precluded this option. Consequently, the measure of predictive capability used in this analysis was the average of the absolute relative deviations for the F-4, F-111, F-14, and F-15. These relative deviations were determined on the basis of the predictive form of the equation and not the logarithmic form used in the regression.[11]

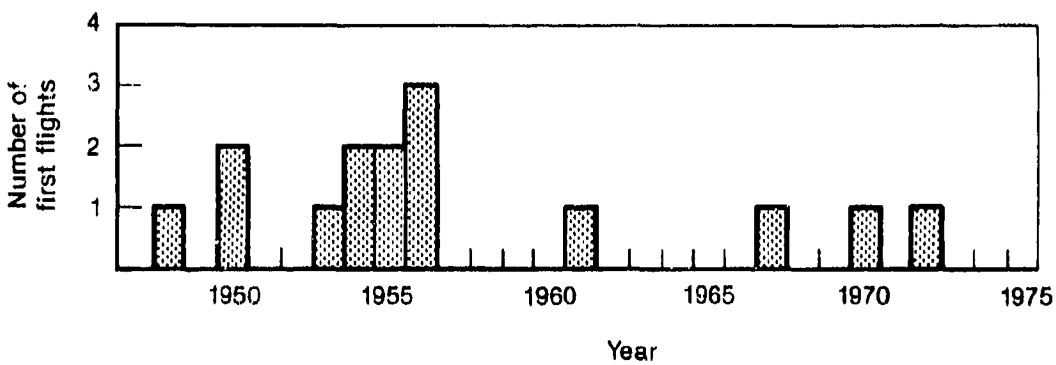

Fig. 2—Number of first flight events as a function of the year of first flight

[11]If cost is estimated in a log-linear form, such as

$$\ell n\ \mathrm{COST} = \beta_0 + \beta_1\ \ell n\ \mathrm{WEIGHT} + \beta_2\ \ell n\ \mathrm{SPEED} + \ell n\ \varepsilon$$

the expected cost is given by

$$\mathrm{COST} = \left(e^{\beta_0}\ \mathrm{WEIGHT}^{\beta_1}\ \mathrm{SPEED}^{\beta_2}\right) \times e^{\hat{\sigma}^2/2}$$

where $\hat{\sigma}^2$ is the actual variance of ε in the log-linear equation. Since the actual variance is not known, the standard error of the estimate may be used as an approximation.

III. INITIAL OBSERVATIONS

This section provides an initial overview of the individual cost element analyses that follow.

MAGNITUDE OF SIZE VARIABLE EXPONENTS

The development of airframe cost-estimating relationships requires variable exponents that provide credible results and conform whenever possible to the normal estimating procedures employed by the airframe industry. Traditionally, airframe weight has always provided returns to scale (that is, increases in airframe size are accompanied by less than proportionate increases in cost).[1] If the opposite phenomenon is observed, then it is generally believed to be the result of not adequately controlling for differences in construction, materials, complexity, and/or other miscellaneous production factors. Unfortunately, many of the regression equations documented in this report possess weight variables with exponents greater than 1.

In each case where a weight exponent greater than 1 was encountered, attempts were made to find variable combinations that would reduce it to less than 1. In some instances success was obtained while in others it was not. In any case, when selecting the representative equation sets, no estimating relationship having a size variable exponent greater than 1 was considered for any of the production-oriented cost elements.[2]

As a point of contrast, it should be noted that estimating relationships based on total aircraft samples do not run into this problem. As shown in Fig. 3, the large aircraft (bombers and transports) *force* the regression line to have a downward slope (on a per

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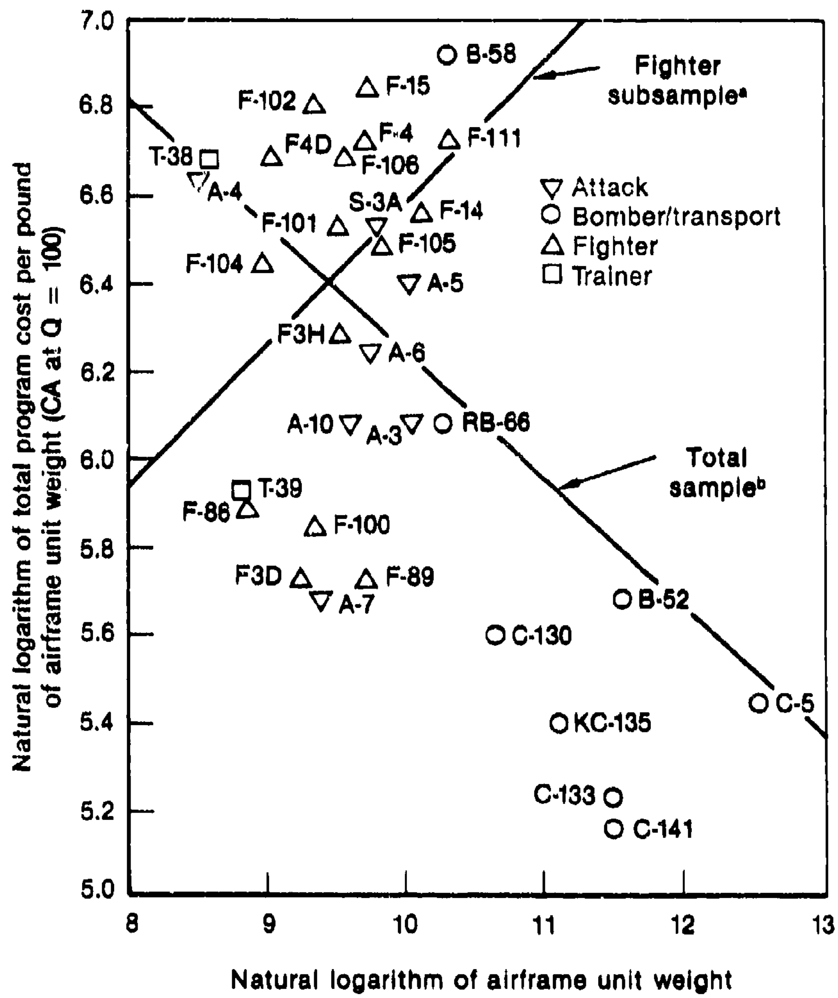
[1]This concept dates back to the early 1940s and the so-called ARCO factor (which took its name from the WWII Aircraft Resources Control Office).

[2]Tooling, manufacturing labor, manufacturing material, and total program cost.



[a]Equivalent to $PROG_{100} = 2.67\ AUW^{1.33}$
[b]Equivalent to $PROG_{100} = 997\ AUW^{0.706}$

Fig. 3—Total program cost per pound as a function of airframe unit weight

pound basis) without having to consider additional explanatory variables.

DATA CLUSTERS

The difficulty in obtaining credible CERs for the full fighter sample resulted in a reexamination of the data. A more thorough examination of the cost-weight plot for each cost element indicated that the fighter data tended to cluster by time period (see Fig. 4):

Pre-1954 (F-86, F-89, F-100, F3D): lower left section of plot

1955-1960 (F3H, F4D, F-101, F-102, F-104, F-105, F-106): middle upper section of plot

Post-1960 (F-4, F-111, F-14, F-15): upper right section of plot

This observation is most pronounced for the engineering, tooling, material, flight test, and total program cost elements.

Unfortunately, we were not able to adequately address the underlying causes of these clusters. However, given our observation regarding the clustering and the fact that the objective of a CER is prediction (as opposed to database explanation), then the post-1960 fighters would certainly seem to be a reasonable guide. Consequently, additional analysis limited to the post-1960 aircraft was undertaken. Since there were only four observations in the post-1960 sample, the equations were determined by visual fitting rather than by statistical analysis. The fitting for each cost element was done on the basis of a single variable--airframe unit weight (except for flight test where the number of test aircraft was utilized).

A comparison of a few of the key variables for the full fighter sample and the post-1960 sample is provided in Table 5. As indicated, the post-1960 group tends to be heavier and higher performing than does the group that contains both the pre-1960 and the post-1960 fighters. Of particular interest is the extremely small amount of speed variation in the post-1960 sample.

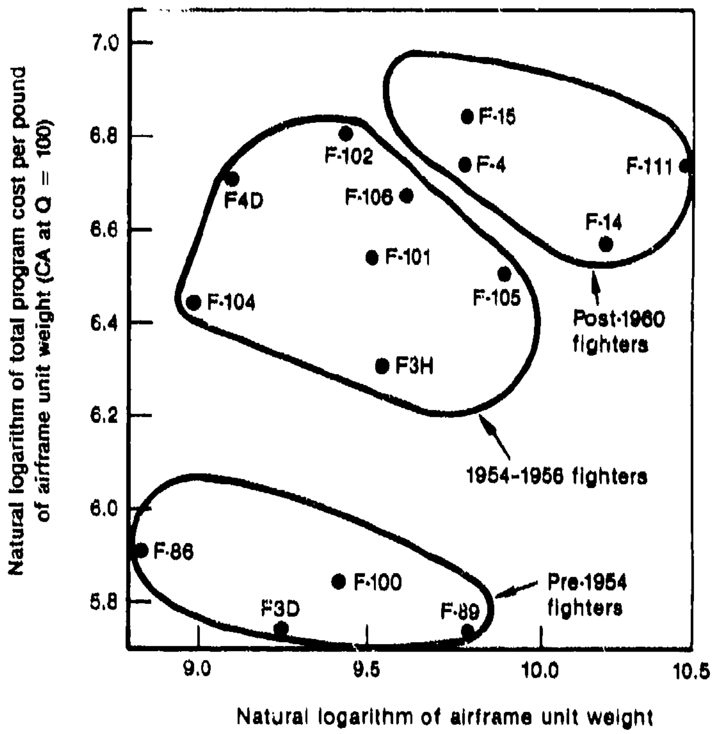


Fig. 4—Typical fighter cluster pattern

Table 5

COMPARISON OF FULL AND POST-1960 FIGHTER SAMPLE VARIABLE VALUES

Variable	Mean		Standard Deviation		Range	
	Full Sample	Post-1960	Full Sample	Post-1960	Full Sample	Post-1960
Airframe unit weight (lb)	15,545	23,605	7,058	7,679	6,788-33,150	17,220-33,150
Empty weight (lb)	23,007	34,330	9,335	9,118	10,040-46,170	26,795-46,170
Wetted area (sq ft)	1,993	2.633	584	412	1,070- 3,155	2,150- 3,155
Speed (kn)	913	1,279	314	46	470- 1,280+	1,222- 1,280+
Specific power (hp/lb)	1.78	2.91	1.02	1.01	0.4- 4+	1.94- 4+
Climb rate (ft/min)	27,850	40,675	17,508	20,981	4,100-50,000+	12,600-50,000+
AVAUW	.107	.096	.054	.013	.016- .215	.081- .112
EWAUW	.52	.48	.16	.11	.27- .84	.39- .60
Number of test aircraft	16	14	7	6	6- 31	7- 20

CONSTRUCTION VARIABLES

The two variables that characterize what goes inside an airframe (the ratio of avionics weight to airframe unit weight and the ratio of the quantity empty weight minus airframe unit weight to airframe unit weight) show up in estimating relationships quite frequently. Consequently, Figs. 5 and 6 are presented in order to illustrate the manner in which these measures vary with airframe size. As shown in these figures, there appears to be little relationship between these measures and airframe unit weight.

TECHNOLOGY INDEX

We were able to identify only one instance (for the engineering cost element) in which the objective technology index was significant at the 5 percent level in the context of the tested variable combination (size/performance/technology index):

$$ENGR_{100} = .00243\ \underset{(.000)}{AUW^{1.13}}\ \underset{(.021)}{SPPWR^{.367}}\ \underset{(.016)}{PFFD^{.697}}$$

R^2	SEE	F	N
.97	.16	134	15

However, the correlation of AUW and SPPWR with the technology index is greater than 0.9. Furthermore, the equation offers little advantage (in terms of the standard error of estimate) over alternative forms without the technology index. We conclude that the objective technology index, as now defined, is of little benefit to fighter airframe CERs. The reason it did so poorly in our analysis is that it is really a composite performance variable and consequently very highly correlated with most of the performance variables we tested here. It should be noted that when the measure is treated as a performance variable rather than as a technology index, it does about as well as speed and specific power as an explanatory variable.

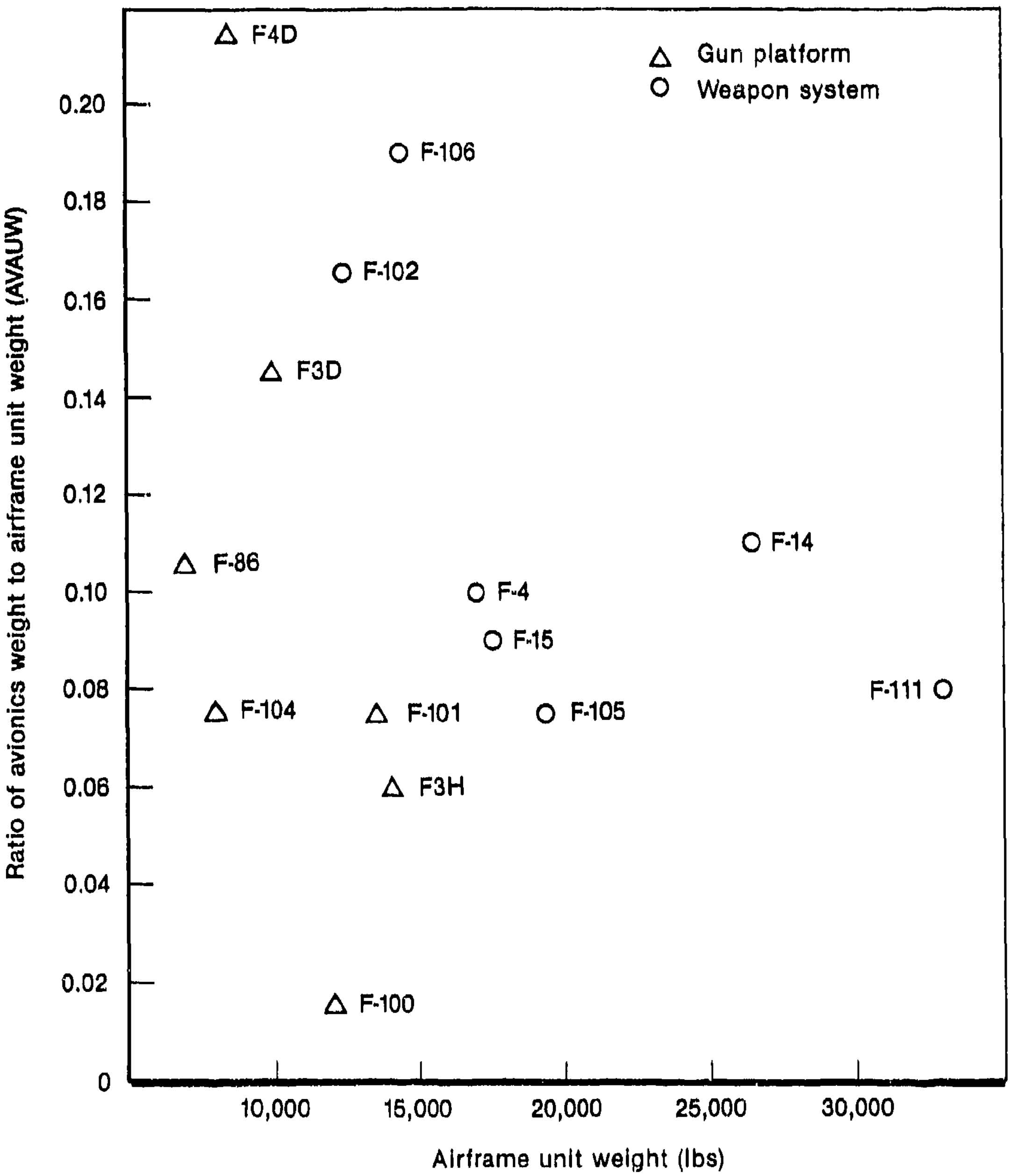


Fig. 5—Ratio of avionics weight to airframe unit weight (AVAUW) as a function of airframe unit weight

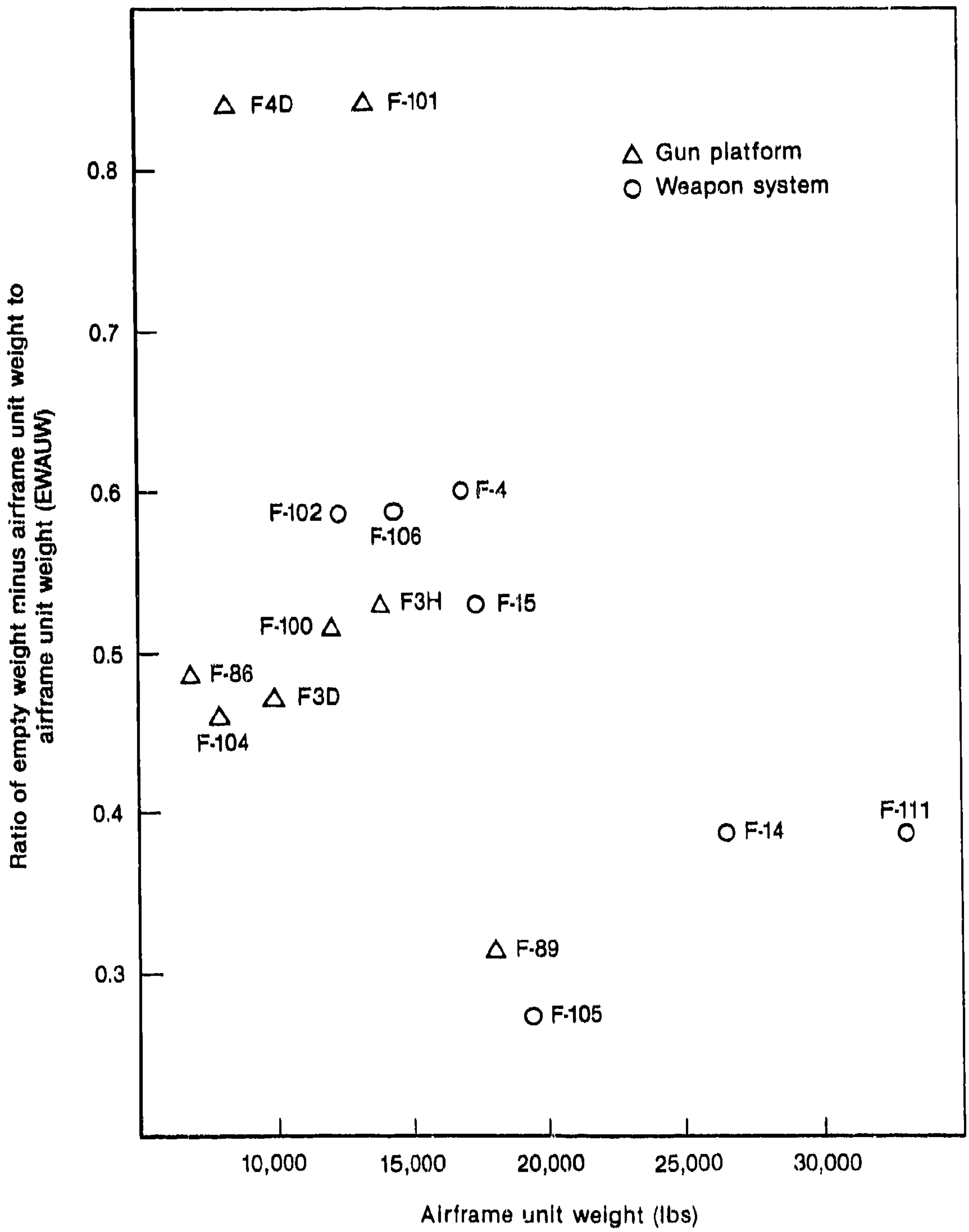


Fig. 6—Ratio of empty weight minus airframe unit weight to airframe unit weight (EWAUW) as a function of airframe unit weight

SET SIZE/PERFORMANCE COMBINATIONS

On the basis of a summary examination of all two-variable estimating relationships (size/performance) for all cost elements, it was decided to develop four distinct equation sets that maintain the integrity of the set size/performance parameters:

- Airframe unit weight and speed
- Airframe unit weight and specific power
- Airframe unit weight and climb rate
- Airframe unit weight and composite performance variable

Generally speaking, the equations containing the size variable wetted area had higher standard errors of estimate and more serious exponent magnitude problems than those equations containing airframe unit weight. Furthermore, the equations containing empty weight also had more serious exponent magnitude problems than those equations containing airframe unit weight.[3]

With respect to the performance parameters, equations incorporating speed, specific power, climb rate, maximum specific energy, and the composite performance variable produced significantly better statistical results than equations incorporating other performance variables. Of the five variables, however, speed, specific power, and climb rate did slightly better than the other two. Therefore, these three variables plus the composite performance variable (because of its unique construction) are carried through in the determination of representative equation sets.

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[3]This is due in large measure to two facts: (a) the F-14 and F-111 are 40 and 70 percent heavier, respectively, than the next largest fighter in the database and thus have a fair amount of leverage in the statistical analysis; and (b) the F-14 and F-111 have higher ratios of airframe unit weight to empty weight, and consequently, when changing from AUW to EW, will not increase in the same proportion as the rest of the database. Thus, visualizing a cost-weight plot, changing from airframe unit weight to empty weight will have the effect of rotating the regression line counterclockwise.

IV. ENGINEERING

Engineering hours per pound are plotted as a function of airframe unit weight in Fig. 7. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 6.

GENERAL OBSERVATIONS

1. With the exception of equations incorporating wetted area (E23-E31), the estimating relationships show a tendency to underestimate the engineering hours of the most recent sample fighters.

2. The exponents of the size variables, with one exception (E28), are always greater than 1 and frequently greater than 1.5.

3. With respect to the construction/program variables:

   (a) As adjuncts to various combinations of size and performance variables, several construction/program variables were determined to be significant at the 5 percent level. However, their incorporation results in relatively modest improvement in the standard error of estimate.

   (b) The variable EWAUW (ratio of empty weight minus airframe unit weight to airframe unit weight) possesses a counter-intuitive sign (E37 and E42).

   (c) The magnitude of the new engine designator (ENGDV) shows a fair amount of variability depending on the size/performance variable combination (from .294 in E32 up to .569 in E40). Furthermore, the magnitude of the ENGDV exponent in equations E34, E36, E38, and E40 may be somewhat high. For example, based on equation E36, a fighter incorporating a new engine will incur 30 percent more engineering hours than a fighter incorporating an off-the-shelf engine.

   (d) The magnitude of the weapon system designator (WSDV) also shows a fair amount of variability depending on the size performance variable combination (from .458 in E39 up to .636 in E41).

4. The equation containing the fighter technology index (E43) has an extremely high degree of intercorrelation (> .9).

REPRESENTATIVE CERS

Airframe Unit Weight and Speed

Only one estimating relationship containing airframe unit weight and speed is listed in Table 6 and that is E4:

$$\text{E4}\quad ENGR_{100} = .0000308\ \underset{(.000)}{AUW^{1.07}}\ \underset{(.000)}{SP^{1.30}}$$

R^2	SEE	F	N	RP
.93	.24	85	15	None

Airframe Unit Weight and Specific Power

Candidate estimating relationships are E6, E32, and E43. Equation E43 is ruled out because of the high degree of intercorrelation. Of the two remaining equations, E6 is selected because of questions regarding the stability of the new engine designator in equation E32:

$$\text{E6}\quad ENGR_{100} = .0290\ \underset{(.000)}{AUW^{1.24}}\ \underset{(.000)}{SPPWR^{.713}}$$

R^2	SEE	F	N	RP
.96	.19	140	15	Cur: Under

Airframe Unit Weight and Climb Rate

Candidate estimating relationships are E7, E33, E34, and E35. Equations E34 and E35 are ruled out because of previously discussed reservations concerning the stability of the new engine and weapon system designator exponents. Equation E33 incorporates the wing type designator. The difficulty in using this variable in a predictive mode is what numerical value to assign to new or to as yet undesignated wing concepts (e.g., forward-swept, variable incidence). Thus, equation E7 is the preferred AVW/CLIMB estimating relationship:

$$\text{E7}\quad ENGR_{100} = .0000396\ \underset{(.000)}{AUW^{1.46}}\ \underset{(.000)}{CLIMB^{.483}}$$

R^2	SEE	F	N	RP
.90	.29	55	15	Cur: Under

Airframe Unit Weight and Composite Performance Index

Only one estimating relationship containing airframe unit weight and the composite performance index is listed in Table 6 and that is E9:

$$\text{E9}\quad ENGR_{100} = .000198\ \underset{(.000)}{AUW^{1.08}}\ \underset{(.000)}{PFFD^{1.28}}$$

R^2	SEE	F	N	RP
.96	.18	146	15	None

Single Best Estimating Relationship

Based on a summary examination of all 43 engineering manhour equations, the list of candidate estimating relationships has been narrowed to E4, E8, E9, E73, and E78. All have relatively low standard errors of estimate and all are free of unusual residual patterns. Equation E9 is arbitrarily selected:

$$\text{E9}\quad ENGR_{100} = .000198\ \underset{(.000)}{AUW^{1.08}}\ \underset{(.000)}{PFFD^{1.28}}$$

R^2	SEE	F	N	RP
.96	.18	146	15	None

Post-1960 Sample

$$ENGR_{100} = 2.31\ AUW^{.887}$$

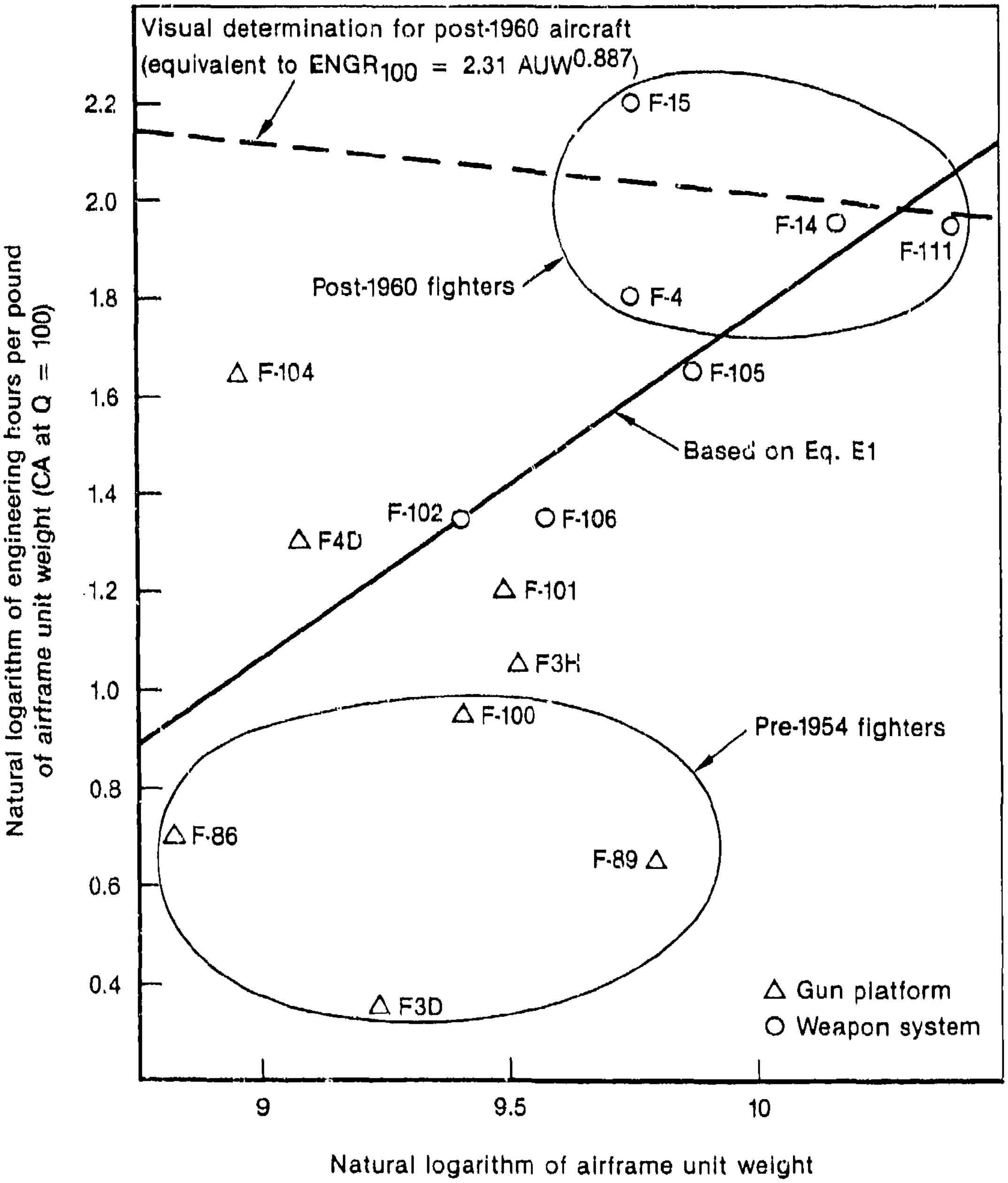

Fig. 7—Engineering hours per pound as a function of airframe unit weight

Table 6

ENGINEERING HOUR ESTIMATING RELATIONSHIPS

Eq. No.	Equation	R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg.	Comments
		Statistics				Relative Deviations (%)					
	SIZE										
E1	$ENGR_{100} = .000580\ \underset{(.000)^{(a)}}{AUW^{1.69}}$	.73	.47	35	15	+20	-11	+7	+46	21	RP:DIST RP:CUR:UNDER EXP MAG:AUW IO:F3D, F-89, F-104, F-15
E2	$ENGR_{100} = .0000673\ \underset{(.000)}{EW^{1.84}}$	.74	.46	37	15	+9	-7	+13	+44	18	RP:DIST RP:CUR:UNDER EXP MAG:EW IO:F3D, F-104, F-15
E3	$ENGR_{100} = .000643\ \underset{(.001)}{WTAREA^{2.14}}$	.58	59	17	14	+18	+45	-4	+17	21	RP:DIST RP:CUR:UNDER EXP MAG:WTAREA IO:F3D, F-104, F-111
	SIZE/PERFORMANCE										
E4	$ENGR_{100} = .0000308\ \underset{(.000)}{AUW^{1.07}}\ \underset{(.000)}{SP^{1.30}}$	.93	.24	85	15	-3	+1	-1	+24	7	IO:F4D
E5	$ENGR_{100} = .0323\ \underset{(.000)}{AUW^{1.21}}\ \underset{(.001)}{SPCLS^{.794}}$	.88	.32	46	15	+2	+1	+7	+35	11	RP:CUR:UNDER IO:F4D
E6	$ENGR_{100} = .0290\ \underset{(.000)}{AUW^{1.24}}\ \underset{(.000)}{SPPWR^{.713}}$	.96	.19	140	15	0	+17	+2	+5	6	RP:DIST RP:CUR:UNDER IO:F-111
E7	$ENGR_{100} = .0000396\ \underset{(.000)}{AUW^{1.46}}\ \underset{(.000)}{CLIMB^{.483}}$	.90	.29	55	15	+4	+35	-8	+21	17	RP:CUR:UNDER IO:F-89, F-111

(a)Variable significance levels are in parentheses.

Table 6 (continued)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg.	Comments
E8	$ENGR_{100} = (5.37 \times 10^{-6})\ \underset{(.000)}{AUW^{1.15}}\ \underset{(.000)}{ENERGY^{1.27}}$	.96	.20	124	14	+3	-12	-5	+10	8	IO:F3D, F4D
E9	$ENGR_{100} = .000198\ \underset{(.000)}{AUW^{1.08}}\ \underset{(.000)}{PFFD^{1.28}}$	.96	.18	146	15	+14	+10	-25	-18	17	IO:F-104, F-14, F-15
E10	$ENGR_{100} = .000401\ \underset{(.000)}{AUW^{1.64}}\ \underset{(.010)}{SUSLD^{.776}}$	.83	.38	29	15	+20	+19	-4	+26	17	RP:CUR:UNDER EXP MAG:AUW IO:F3D, F-104, F-111
E11	$ENGR_{100} = .00619\ \underset{(.000)}{AUW^{1.50}}\ \underset{(.000)}{THWT^{1.18}}$	.92	.25	74	15	+8	+25	+5	-1	10	RP:DIST RP:CUR:UNDER EXP MAG:AUW IO:F-86, F-89, F-104, F-111
E12	$ENGR_{100} = .00645\ \underset{(.000)}{AUW^{1.56}}\ \underset{(.050)}{USELD^{1.43}}$	.78	.43	22	15	+8	-25	+9	+40	20	EXP MAG:AUW RP:CUR:UNDER IO:F3D, F-89, F-104, RP:DIST
E13	$ENGR_{100} = .00000874\ \underset{(.000)}{EW^{1.17}}\ \underset{(.000)}{SF^{1.28}}$	.94	.24	87	15	-12	+3	+4	+23	10	
E14	$ENGR_{100} = .00624\ \underset{(.000)}{EW^{1.32}}\ \underset{(.001)}{SPCLS^{.78}}$	.89	.30	50	15	-7	+3	+11	+33	14	RP:DIST RP:CUR:UNDER IO:F-104
E15	$ENGR_{100} = .00828\ \underset{(.000)}{EW^{1.32}}\ \underset{(.000)}{SPPWR^{.669}}$	.93	.25	79	15	-8	+20	+9	+6	11	RP:DIST RP:CUR:UNDER IO:F-104, F-111

Table 6 (continued)

Eq. No.	Equation	R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg.	Comments
		Statistics				Relative Deviations (%)					
E16	$ENGR_{100} = .0000107\ \underset{(.000)}{EW^{1.57}}\ \underset{(.001)}{CLIMB^{.447}}$	.88	.32	46	15	-6	+36	0	+20	16	EXP MAG:EW RP:DIST RP:CUR:UNDER IO:F-86, F-104, F-111
E17	$ENGR_{100} = (1.08 \times 10^{-8})\ \underset{(.000)}{EW^{1.20}}\ \underset{(.000)}{ENERGY^{1.33}}$	.96	.20	121	14	-5	-7	+2	+6	5	
E18	$ENGR_{100} = .0000699\ \underset{(.000)}{EW^{1.16}}\ \underset{(.000)}{PFFD^{1.25}}$	.95	.21	111	15	+7	+13	-17	-19	14	IO:F-89, F-104, F-15
E19	$ENGR_{100} = .0000715\ \underset{(.000)}{EW^{1.76}}\ \underset{(.024)}{SUSLD^{.667}}$	.81	.40	26	15	+9	+20	+5	+26	15	RP:DIST RP:CUR:UNDER EXP MAG:EW IO:F-104, F-111
E20	$ENGR_{100} = .00139\ \underset{(.000)}{EW^{1.58}}\ \underset{(.002)}{THWT^{.993}}$	.87	.33	40	15	0	+26	+13	+5	11	RP:DIST RP:CUR:UNDER EXP MAG:EW IO:F-104, F-111
E21	$ENGR_{100} = (6.52 \times 10^{-9})\ \underset{(.000)}{EW^{1.47}}\ \underset{(.038)}{BREG^{1.52}}$	.80	.41	24	15	+34	-23	-12	+41	28	IO:F-86, F-4, F-104
E22	$ENGR_{100} = .000867\ \underset{(.000)}{EW^{1.69}}\ \underset{(.045)}{USELD^{1.44}}$	.80	.42	23	15	-4	-22	+14	+38	20	RP:CUR:UNDER EXP MAG:EW IO:F3D, F-104
E23	$ENGR_{100} = .00000869\ \underset{(.001)}{WTAREA^{1.23}}\ \underset{(.000)}{SP^{1.62}}$	.91	.29	53	14	-8	+35	-9	-2	14	IO:F3D, F-106, F-111

Table 6 (continued)

Eq. No.	Equation	R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg.	Comments
		Statistics				Relative Deviations (%)					
E24	$ENGR_{100} = .0775\ \underset{(.003)}{WTAREA^{1.40}}\ \underset{(.001)}{SPCLS^{1.00}}$	.82	.41	25	14	-2	+40	+2	+12	14	RP:DIST RP:CUR:UNDER IO:F3D
E25	$ENGR_{100} = .0837\ \underset{(.001)}{WTAREA^{1.43}}\ \underset{(.000)}{SPPWR^{.829}}$	.86	.35	35	14	-2	+53	-2	-34	23	IO:F-111
E26	$ENGR_{100} = .0000537\ \underset{(.001)}{WTAREA^{1.79}}\ \underset{(.007)}{CLIMB^{.501}}$	.76	.47	18	14	+3	+66	-16	-14	25	EXP MAG:WTAREA IO:F-3D,F-104, F-111
E27	$ENGR_{100} = (3.16 \times 10^{-9})\ \underset{(.000)}{WTAREA^{1.28}}\ \underset{(.000)}{ENERGY^{1.64}}$	.91	.28	59	14	+1	+29	-11	-30	18	EXP MAG:ENERGY IO:F3D
E23	$ENGR_{100} = .000507\ \underset{(.012)}{WTAREA^{.957}}\ \underset{(.000)}{PFFD^{1.70}}$	.88	.33	41	14	+15	+46	-30	-77	42	EXP MAG:PFFD IO:F3D,F-111, F-15
E29	$ENGR_{100} = .000508\ \underset{(.001)}{WTAREA^{2.07}}\ \underset{(.048)}{SUSLD^{.748}}$	.68	.54	12	14	+18	+59	-14	-11	26	EXP MAG:WTAREA IO:F3D,F-104, F-111
E30	$ENGR_{100} = .0143\ \underset{(.001)}{WTAREA^{1.80}}\ \underset{(.013)}{THWT^{1.11}}$	.74	.49	16	14	+9	+60	+1	-38	27	EXP MAG:WTAREA IO:F3D,F-104, F-111
E31	$ENGR_{100} = (2.09 \times 10^{-9})\ \underset{(.010)}{WTAREA^{1.54}}\ \underset{(.042)}{BREG^{2.02}}$	.69	.54	12	14	+46	+22	-35	+22	31	EXP MAG:WTAREA EXP MAG:BREG IO:F3D,F-86, F-4,F-104

Table 6 (continued)

Eq. No.	Equation	R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg.	Comments
	SIZE/PERFORMANCE/CONSTRUCTION, PROGRAM										
E32	$ENGR_{100} = .0150\ \underset{(.000)}{AUW^{1.30}}\ \underset{(.000)}{SPPWR^{.670}}\ \underset{(.018)}{ENGDV^{.294}}$	.97	.16	132	15	+11	+4	+10	-2	7	RP:CUR:UNDER
E33	$ENGR_{100} = .000154\ \underset{(.000)}{AUW^{1.36}}\ \underset{(.001)}{CLIMB^{.408}}\ \underset{(.025)}{WGTYPE^{.415}}$	.93	.25	50	15	+14	+20	-23	+31	22	IO:F-111,F-15
E34	$ENGR_{100} = .0000220\ \underset{(.000)}{AUW^{1.52}}\ \underset{(.000)}{CLIMB^{.465}}\ \underset{(.011)}{ENGDV^{.477}}$	.94	.24	58	15	+19	+19	+6	+7	13	RP:CUR:UNDER EXP MAG:AUW IO:F-111
E35	$ENGR_{100} = .000932\ \underset{(.000)}{AUW^{1.20}}\ \underset{(.001)}{CLIMB^{.401}}\ \underset{(.045)}{WSDV^{.546}}$	.93	.27	45	15	-6	+34	-5	+17	16	MCOL:r(WSDV) > .7 IO:F-104,F-111
E36	$ENGR_{100} = (5.15 \times 10^{-6})\ \underset{(.000)}{EW^{1.29}}\ \underset{(.000)}{SP^{1.15}}\ \underset{(.020)}{ENGDV^{.374}}$	.96	.20	82	15	+3	-16	+14	+14	12	EXP MAG:ENGDV
E37	$ENGR_{100} = .0196\ \underset{(.000)}{EW^{1.19}}\ \underset{(.000)}{SPPWR^{.729}}\ \underset{(.009)}{EWAUW^{-.493}}$	.96	.20	84	15	+3	+18	+2	+6	7	RP:DIST RP:CUR:UNDER EXP SIGN:EWAUW IO:F-101,F-111
E38	$ENGR_{100} = .00235\ \underset{(.000)}{EW^{1.43}}\ \underset{(.000)}{SPPWR^{.601}}\ \underset{(.020)}{ENGDV^{.389}}$	.95	.21	74	15	+7	+2	+18	-3	8	EXP MAG:ENGDV RP:DIST RP:CUR:UNDER IO:F-104
E39	$ENGR_{100} = .0497\ \underset{(.000)}{EW^{1.13}}\ \underset{(.000)}{SPPWR^{.567}}\ \underset{(.050)}{WSDV^{.458}}$	.95	.23	64	15	-14	+21	+9	+4	12	MCOL:r(WSDV) > .7 RP:CUR:UNDER IO:F-101,F-104, F-111

Table 6 (continued)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg.	Comments
E40	$ENGR_{100} = (3.93 \times 10^{-6})\ \underset{(.000)}{EW^{1.68}}\ \underset{(.000)}{CLIMB^{.419}}\ \underset{(.005)}{ENGDV^{.569}}$	.94	.24	55	15	+13	+4	+16	+4	12	RP:DIST RP:CUR:UNDER EXP MAG:EW EXP MAG:ENGDV IO:F-104,F-111
E41	$ENGR_{100} = .000520\ \underset{(.000)}{EW^{1.25}}\ \underset{(.004)}{CLIMB^{.357}}\ \underset{(.029)}{WSDV^{.636}}$	.92	.28	41	15	-16	+34	+2	+15	17	MCOL:r(WSDV) > .7 RP:CUR:UNDER IO:F-104,F-111
E42	$ENGR_{100} = .0000949\ \underset{(.000)}{EW^{1.09}}\ \underset{(.000)}{PFFD^{1.29}}\ \underset{(.030)}{EWAUW^{-.345}}$	.96	.19	96	15	+14	+10	-24	-18	16	EXP SIGN:EWAUW IO:F-104
	SIZE/PERFORMANCE/TECHNOLOGY INDEX										
E43	$ENGR_{100} = .00242\ \underset{(.000)}{AUW^{1.13}}\ \underset{(.021)}{SPPWR^{.367}}\ \underset{(.016)}{PFFD^{.699}}$	.97	.16	134	15	+7	+15	-12	-11	11	MCOL:r(PFFD) > .9 IO:F-111

V. TOOLING

Tooling hours per pound are plotted as a function of airframe unit weight in Fig. 8. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 7.

GENERAL OBSERVATIONS

1. Only one equation possesses a standard error of estimate of less than 30 percent and that one (T27) contains a variable with a counterintuitive sign.

2. The magnitude of the wetted area exponent (T16-T20) is in every case greater than or equal to one.

3. With respect to the construction/program variables:

   (a) The sign of the wing area to wetted area variable (WGWET) is counterintuitive (T21 through T25, and T27).

   (b) The magnitudes of the contractor experience designator (EXPDV in T26), the weapon system designator (WSDV in T30), and the prototype program designator (PRGDV in T31) all seem fairly large. For example, a contractor without experience would incur tooling costs 56 percent greater than a contractor with experience; a weapon system would incur tooling costs 75 percent greater than a gun platform; and a prototype program would incur tooling costs 40 percent less than a concurrent program.

   (c) The equations containing the wing type designator (T28 and T29) present an unusual problem. A quick inspection (see Fig. 9) indicates that both variable sweep aircraft are overestimated while all three delta-wing aircraft are underestimated. This suggests that perhaps the rank-ordering of the two wing types should be reversed. However, at this time, no logical basis exists for making such a reversal.

   (d) The variable "maximum tooling capability" was not found to be significant at the 5 percent level in any equation form.

4. The fighter technology index was not found to be significant at the 5 percent level in the required equation form (size/performance/ technology index).

REPRESENTATIVE CERS

Airframe Unit Weight and Speed

Candidate estimating relationships are T4 and T21. Equation T21 is eliminated because it contains a variable (WGWET) with a counterintuitive sign.

$$\text{T4}\quad \frac{\text{TOOL}}{100} = .0981\ \underset{(.026)}{\text{AUW}^{.627}}\ \underset{(.027)}{\text{SP}^{.740}}$$

R^2	SEE	F	N	RP
.64	.39	11	15	None

Airframe Unit Weight and Specific Power

Candidate estimating relationships are T6 and T22. Equation T22 is eliminated because it contains a variable (WGWET) with a counterintuitive sign.

$$\text{T6}\quad \frac{\text{TOOL}}{100} = 5.93\ \underset{(.007)}{\text{AUW}^{.700}}\ \underset{(.010)}{\text{SPPWR}^{.444}}$$

R^2	SEE	F	N	RP
.69	.36	13	15	None

Airframe Unit Weight and Climb Rate

Candidate estimating relationships are T7 and T23. Equation T23 is eliminated because it contains a variable (WGWET) with a counterintuitive sign.

$$\text{T7}\ \frac{\text{TOOL}}{100} = .110\ \underset{(.003)}{\text{AUW}^{.846}}\ \underset{(.038)}{\text{CLIMB}^{.278}}$$

R^2	SEE	F	N	RP
.62	.40	10	15	None

Airframe Unit Weight and Composite Performance Index

Only one estimating relationship containing airframe unit weight and the composite performance index is listed in Table 7: T8:

$$\text{T8}\ \frac{\text{TOOL}}{100} = .295\ \underset{(.020)}{\text{AUW}^{.657}}\ \underset{(.027)}{\text{PFFD}^{.684}}$$

R^2	SEE	F	N	RP
.64	.39	11	15	None

Single Best Estimating Relationship

Based on a summary examination of all 31 tooling manhour equations, the list of candidate estimating relationship has been narrowed to T6, T9, T12, and T15. Equation T12 is selected on the basis of the lowest standard error of estimate:

$$\text{T12}\ \frac{\text{TOOL}}{100} = .876\ \underset{(.003)}{\text{EW}^{.865}}\ \underset{(.017)}{\text{SPPWR}^{.382}}$$

R^2	SEE	F	N	RP
.73	.33	17	15	None

Post-1960 Sample

$$TOOL_{100} = 1.38\ AUW^{.883}$$

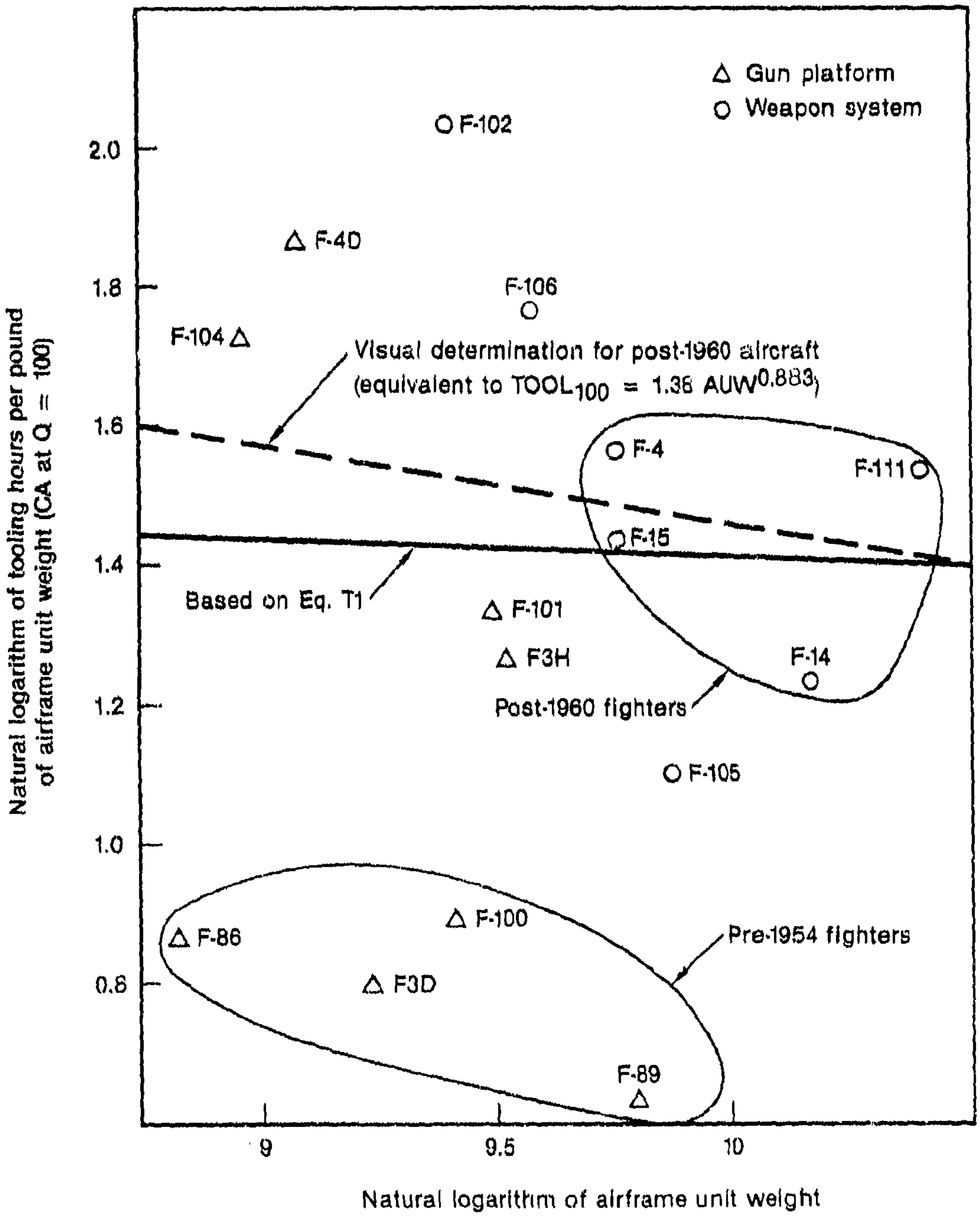

Fig. 8—Tooling hours per pound as a function of airframe unit weight

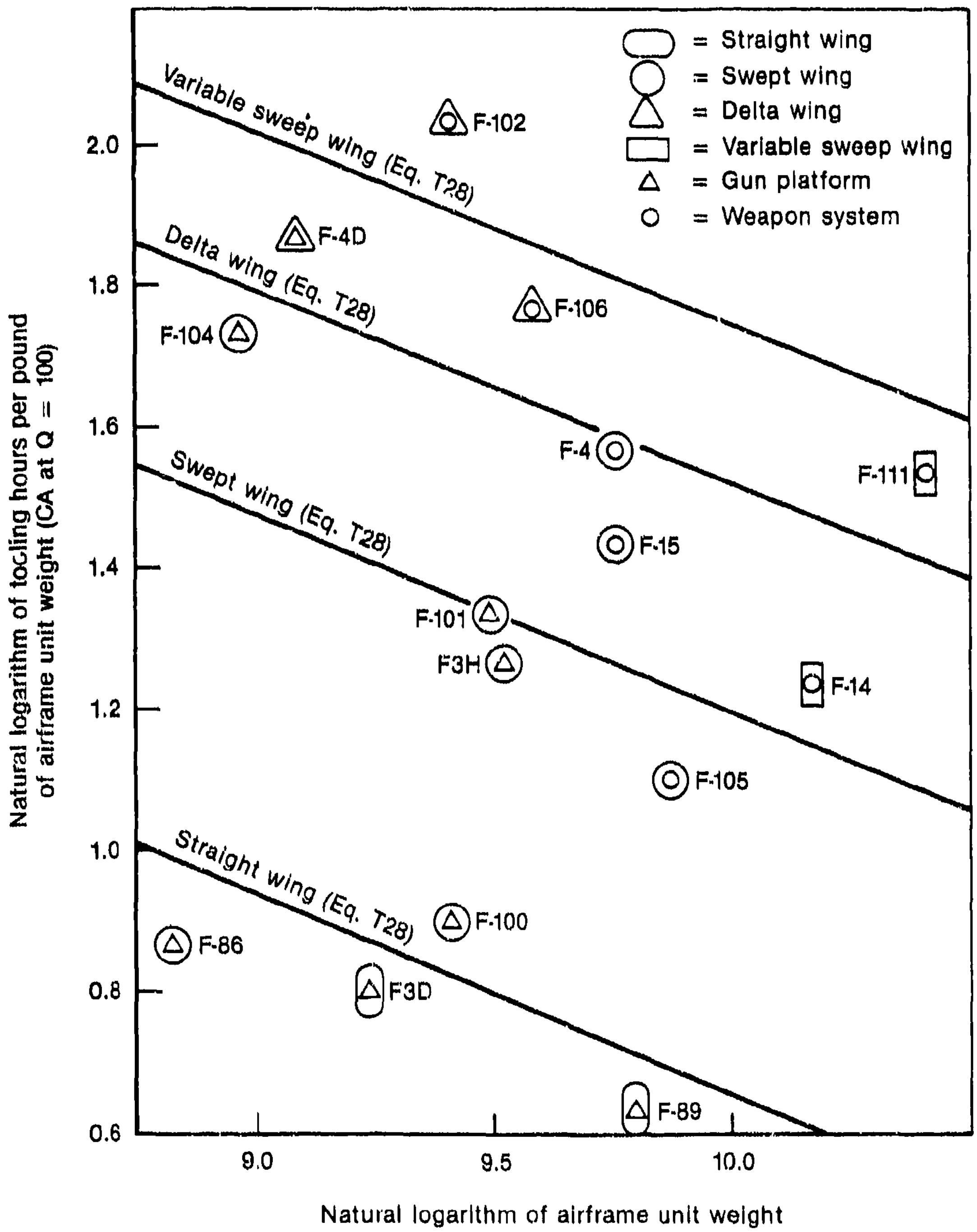

Fig. 9—Tooling hours per pound as a function of airframe unit weight and wing type

Table 7

TOOLING HOUR ESTIMATING RELATIONSHIPS

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg	Comments
	SIZE										
T1	$TOOL_{100} = .507\ AUW^{.980}$ (.002)	.50	.44	13	15	+12	+11	-22	+2	12	IO:F3D,F4D,F-86 F-89,F-102, F-104
T2	$TOOL_{100} = .0549\ EW^{1.16}$ (.000)	.61	.39	20	15	+5	+7	-22	-1	9	EXP MAG:EW IO:F3D,F-86, F-102,F-104
T3	$TOOL_{100} = .135\ WTAREA^{1.42}$ (.001)	.54	.43	14	14	+12	+39	-39	-30	30	EXP MAG:WTAREA IO:F3D,F-86, F-104,F-111
	SIZE/PERFORMANCE										
T4	$TOOL_{100} = .0981\ AUW^{.627}\ SP^{.740}$ (.026) (.027)	.64	.39	11	15	-4	+14	-31	-22	18	IO:F-86
T5	$TOOL_{100} = 6.91\ AUW^{.670}\ SPCLS^{.512}$ (.018) (.028)	.64	.39	11	15	-2	+16	-24	-13	14	IO:F4D
T6	$TOOL_{100} = 5.93\ AUW^{.700}\ SPPWR^{.444}$ (.007) (.010)	.69	.36	13	15	-3	+24	-30	-43	25	IO:F-111
T7	$TOOL = .110\ AUW^{.846}\ CLIMB^{.278}$	.62	.40	10	15	+1	+33	-36	-25	24	IO:F-111

Table 7 (continued)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg	Comments
T8	$TOOL_{100} = .295\ AUW^{.657}_{(.020)}\ PFFD^{.684}_{(.027)}$	.64	.39	11	15	+6	+18	-47	-54	31	IO: F-86, F-15
T9	$TOOL_{100} = 2.56\ AUW^{.855}_{(.001)}\ THWT^{.800}_{(.010)}$	.69	.36	13	15	+2	+30	-27	-53	28	IO: F-111, F-15
T10	$TOOL_{100} = .0204\ EW^{.827}_{(.007)}\ SP^{.635}_{(.033)}$	.71	.35	14	15	-8	+10	-31	-21	18	IO: F-86, F-102
T11	$TOOL_{100} = .761\ EW^{.865}_{(.004)}\ SPCLS^{.454}_{(.029)}$	.71	.35	15	15	-6	+11	-25	-14	14	IO: F4D
T12	$TOOL_{100} = .876\ EW^{.865}_{(.003)}\ SPPWR^{.382}_{(.017)}$	.73	.33	17	15	-7	+20	-28	-39	24	IO: F-111
T13	$TOOL_{100} = .0208\ EW^{1.02}_{(.001)}\ CLIMB^{.240}_{(.046)}$	.69	.36	14	[illegible]	-5	+28	-33	-24	22	EXP MAG: EW IO: F-104, F-111
T14	$TOOL_{100} = .0573\ EW^{.850}_{(.006)}\ PFFD^{.576}_{(.040)}$	.70	.36	14	15	+2	+14	-43	-46	26	IO: F-86, F-104, F-15
T15	$TOOL = .411\ EW^{.994}\ TEWT^{.656}$	.72	.34	16	15	-2	+26	-23	-45	24	IO: F-111, F-15

Table 7 (continued)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg	Comments
T16	$TOOL_{100} = .0195\ \underset{(.011)}{WTAREA^{1.00}}\ \underset{(.024)}{SP^{.742}}$	.68	.37	12	14	-4	+32	-47	-48	33	IO:F3D,F-86, F-102,F-104
T17	$TOOL_{100} = 1.57\ \underset{(.010)}{WTAREA^{1.04}}\ \underset{(.032)}{SPCLS^{.508}}$	.67	.38	11	14	-1	+34	+38	-38	28	EXP MAG:WTAREA IO:F3D,F4D, F-104
T18	$TOOL_{100} = 1.69\ \underset{(.006)}{WTAREA^{1.05}}\ \underset{(.018)}{SPPWR^{.426}}$	.70	.36	13	14	-2	+42	-42	-72	40	EXP MAG:WTAREA IO:F3D,F-104, F-15
T19	$TOOL_{100} = .000531\ \underset{(.009)}{WTAREA^{1.03}}\ \underset{(.023)}{ENERGY^{.747}}$	.69	.37	12	14	0	+29	-49	-66	36	EXP MAG:WTAREA IO:F3D,F-86, F-102,F-104, F-15
T20	$TOOL_{100} = .867\ \underset{(.003)}{WTAREA^{1.2?}}\ \underset{(.040)}{THWT^{.662}}$	.66	.39	11	14	+5	+49	-37	-78	42	EXP MAG:WTAREA IO:F3D,F-104, F-111,F-15
	<u>SIZE/PERFORMANCE/CONSTRUCTION, PROGRAM</u>										
T21	$TOOL_{100} = .0397\ \underset{(.006)}{AUW^{.848}}\ \underset{(.027)}{SP^{.787}}\ \underset{(.020)}{WGWET^{1.07}}$	.77	.33	11	14	-15	+11	-14	-26	16	RP:DIST MCOL:r(SP) > .7 EXP SIGN:WGWET EXP MAG:WGWET IO:F-104
T22	$TOOL_{100} = 2.14\ \underset{(.002)}{AUW^{.943}}\ \underset{(.019)}{SPPWR^{.398}}\ \underset{(.032)}{WGWET^{.881}}$	.79	.32	12	14	-10	+18	-16	-41	21	RP:DIST EXP SIGN:WGWET IO:F-104

Table 7 (continued)

Eq. No.	Equation	R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg	Comments
		Statistics				Relative Deviations (%)					
T23	$TOOL_{100} = .0473\ \underset{(.000)}{AUW^{1.10}}\ \underset{(.036)}{CLIMB^{.257}}\ \underset{(.035)}{WGWET^{.911}}$	.76	.34	11	14	-9	+26	-23	-28	22	EXP SIGN:WGWET EXP MAG:AUW IO:F-104, F-111
T24	$TOOL_{100} = .000778\ \underset{(.004)}{AUW^{.877}}\ \underset{(.019)}{ENERGY^{.802}}\ \underset{(.017)}{WGWET^{1.08}}$	.79	.32	12	14	-11	+5	-15	-42	18	RP:D[illegible] EXP [illegible]N:WGWET IO:F-86, F-104
T25	$TOOL_{100} = .0123\ \underset{(.003)}{EW^{.935}}\ \underset{(.025)}{SP^{.745}}\ \underset{(.027)}{WGWET^{.908}}$	.81	.31	14	14	-19	+11	-13	-26	17	EXP SIGN:WGWET IO:F-104
T26	$TOOL_{100} = 12.4\ \underset{(.030)}{EW^{.574}}\ \underset{(.004)}{SPPWR^{.643}}\ \underset{(.040)}{EXPDV^{.680}}$	.80	.30	15	15	0	+5	-11	-50	16	EXP MAG:EXPDV MCOL: r(SPPWR) > .7 IO:F3H, F-102
T27	$TOOL_{100} = .000259\ \underset{(.001)}{EW^{.959}}\ \underset{(.016)}{ENERGY^{.766}}\ \underset{(.022)}{WGWET^{.916}}$	.82	.29	15	14	-15	+6	-14	-42	19	RP:DIST EXP SIGN:WGWET IO:F-86, F-104
	SIZE/CONSTRUCTION, PROGRAM										
T28	$TOOL_{100} = 2.99\ \underset{(.002)}{AUW^{.726}}\ \underset{(.002)}{WGTYPE^{.787}}$	.75	.32	18	15	+25	-11	-61	+17	28	IO:F-86, F-14
T29	$TOOL_{100} = .595\ \underset{(.001)}{EW^{.864}}\ \underset{(.004)}{WGTYPE^{.692}}$	.79	.30	22	15	+19	-9	-54	+14	24	IO:F-86, F-104, F-14

Table 7 (continued)

Eq. No.	Equation	Statistics				Relative Deviations (%)					Comments
		R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg	
T30	$TOOL_{100} = 4.80\ \underset{(.019)}{EW^{.684}}\ \underset{(.015)}{WSDV^{.808}}$	.74	.33	17	15	-11	+15	-24	-20	18	EXP MAG:WSDV IO:F-86, F-104
T31	$TOOL_{100} = 7.20\ \underset{(.030)}{EW^{.694}}\ \underset{(.037)}{PRGDV^{-.735}}$	.70	.35	14	15	-6	+19	-18	-14	14	MCOL: r(PRGDV) > .7 EXP MAG: PRGDV IO:F-86, F-104
	<u>SIZE/PERFORMANCE/TECHNOLOGY INDEX</u>										
	None										

VI. MANUFACTURING LABOR

Manufacturing labor hours per pound are plotted as a function of airframe unit weight in Fig. 10. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 8.

GENERAL OBSERVATIONS

1. In all but three equations (L8, L10, and L11), the magnitude of the size variable exponent is greater than or equal to 1.

2. Only two equations were identified in which performance variables were significant and in both cases the magnitude of the size variable was greater than or equal to 1.

3. The standard errors of estimate were clustered between .27 and .35.

4. With respect to the construction/program variables:

(a) No estimating relationships were identified in which construction/program variables appeared in conjunction with a size/performance variable combination.

(b) The weapon system designator (WSDV) in Equations in L8, L10, and L11 indicates that a fighter with missile armament and a sophisticated fire control system will incur 40 to 45 percent higher labor costs than will a fighter that is simply a gun platform.

(c) The avionics to airframe unit weight variable in Equations L7 and L9 indicates that a 50 percent increase in the ratio will result in roughly 10 percent increase in labor costs.

(d) The variable EWAUW (ratio of empty weight minus airframe unit weight to airframe unit weight) in Equations L6 and L11 indicates that a 50 percent increase in the ratio will result in a 20 to 25 percent increase in labor costs.

(e) The variable "maximum tooling capability" was not found to be significant at the 5 percent level on any equation form.

5. The fighter technology index was not found to be significant at the 5 percent level in the required equation form (size/performance/ technology index).

REPRESENTATIVE CERS

Airframe Unit Weight and Speed

No estimating relationships containing this size/performance variable combination were identified.

Airframe Unit Weight and Specific Power

No estimating relationships containing this size/performance variable combination were identified.

Airframe Unit Weight and Climb Rate

No estimating relationships containing this size/performance variable combination were identified.

Airframe Unit Weight and Composite Performance Index

No estimating relationships containing this size/performance variable combination were identified.

Single Best Estimating Relationship

Based on a summary examination of all 11 manufacturing labor manhour equations, the list of candidate estimating relationships has been narrowed to L8, L10, and L11. Equation L8 is selected because it most closely corresponds to our expectations concerning the magnitude of the size variable:

$$\text{L8} \quad LABR_{100} = 6.55 \; \underset{(.005)}{AUW^{.774}} \; \underset{(.049)}{WSDV^{.558}}$$

R^2	SEE	F	N	RP
.75	.31	18	15	None

Post-1960 Sample

The following equation was visually fit to the data with the F-4 observation essentially ignored. Inclusion of the F-4 would have resulted in an equation with an exponent far too small to be credible (for each doubling of weight, total labor hours would have increased by only about 20 percent).

$$LABR_{100} = 23.0\ AUW^{.678}$$

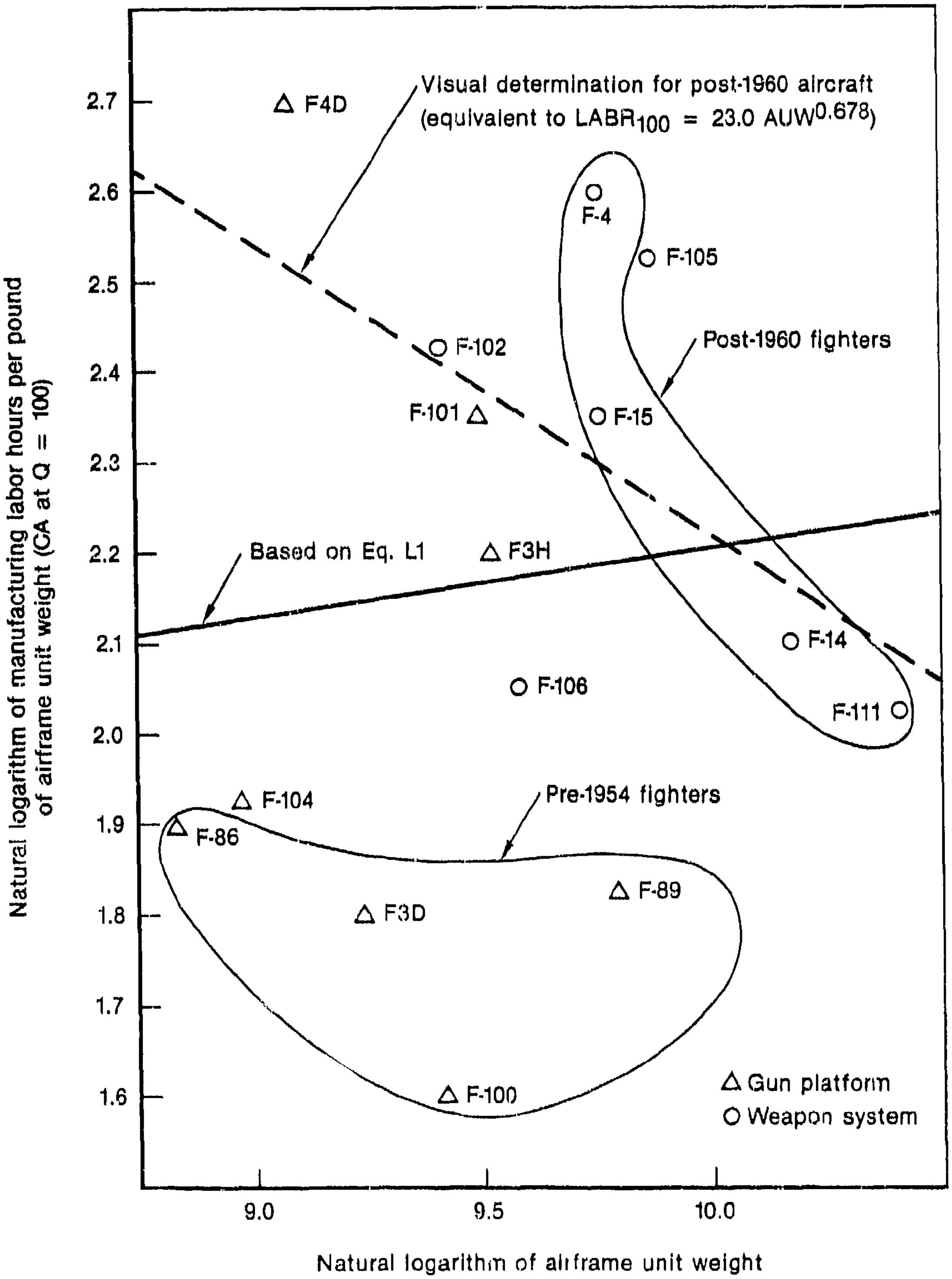

Fig. 10--Manufacturing labor hours per pound as a function of airframe unit weight

Table 8

MANUFACTURING LABOR HOUR ESTIMATING RELALTIONSHIPS

Eq. No.	Equation	Statistics				Relative Deviations (%)					Comments
		R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg.	
	SIZE										
L1	$LABR_{100} = .411\ \underset{(.000)}{AUW^{1.08}}$	.68	.33	27	15	+31	-30	-17	+11	22	EXP MAG:AUW IO:F4D,F-100,F-111
L2	$LABR_{100} = .0577\ \underset{(.000)}{EW^{1.23}}$	.76	.29	41	15	+25	-32	-15	+8	20	EXP MAG:EW IO:F4D,F-100,F-105, F-111
L3	$LABR_{100} = .125\ \underset{(.000)}{WTAREA^{1.53}}$	.67	.35	24	14	+32	+17	-30	-18	24	EXP MAG:WTAREA IO:F3D,F4D,F-105
	SIZE/PERFORMANCE										
L4	$LABR_{100} = 1.18\ \underset{(.000)}{AUW^{1.00}}\ \underset{(.029)}{THWT^{.516}}$	.76	.30	19	15	+25	-13	-21	-20	20	RP:CUR:OVER IO:F4D
L5	$LABR_{100} = .743\ \underset{(.000)}{WTAREA^{1.42}}\ \underset{(.047)}{USELD^{1.24}}$	.74	.32	16	14	+24	+3	-27	-26	20	EXP MAG:WTAREA EXP MAG:USELD
	SIZE/CONSTRUCTION, PROGRAM										
L6	$LABR_{100} = .124\ \underset{(.000)}{AUW^{1.25}}\ \underset{(.048)}{EWAUW^{.531}}$	.75	.31	18	15	+22	-30	-13	+5	18	EXP MAG:AUW IO:F4D,F-105

Table 8 (continued)

Eq. No.	Equation	R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg	Comments
		Statistics				Relative Deviations (%)					
L7	$LABR_{100} = .378\ \underset{(.000)}{AUW^{1.16}}\ \underset{(.040)}{AVAUW^{.253}}$	.78	.30	20	14	+27	-36	-31	+8	26	EXP MAG:AUW IO:F4D,F-100,F-111
L8	$LABR_{100} = 6.55\ \underset{(.005)}{AUW^{.774}}\ \underset{(.049)}{WSDV^{.558}}$	.75	.31	18	15	+21	-22	-18	-2	16	IO:F4D
L9	$LABR_{100} = .0740\ \underset{(.000)}{EW^{1.26}}\ \underset{(.053)}{AVAUW^{.209}}$	.82	.27	25	14	+22	-33	-22	+7	21	EXP MAG:EW VAR SIG:AVAUW IO:F-100,F-111
L10	$LABR_{100} = .819\ \underset{(.001)}{EW^{.952}}\ \underset{(.049)}{WSDV^{.479}}$	.81	.27	26	15	+17	-26	-17	-3	16	
L11	$LABR_{100} = 1.74\ \underset{(.002)}{AUW^{.950}}\ \underset{(.050)}{EWAUW^{.489}}\ \underset{(.051)}{WSDV^{.512}}$	.80	.28	15	15	+12	-23	-14	-6	14	MCOL:r(AUW) > .7 VAR SIG:WSDV RP:CUR:UNDER IO:F4D,F-105

SIZE/PERFORMANCE/TECHNOLOGY INDEX

None

VII. MANUFACTURING MATERIAL

Manufacturing material cost per pound is plotted as a function of airframe unit weight in Fig. 11. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 9.

GENERAL OBSERVATIONS

1. The magnitude of the size variable exponent is greater than 1 in all but one equation (M41). No combination of variables could be found that would bring it below 1 (although the weapon system designator did bring it down to 1).

2. Estimating relationships without a performance variable (M1, M2, M3, M41, M42, M43) show a tendency to underestimate the material costs of the most recent fighters.

3. With respect to construction/program variables:

(a) Two construction variables show up repeatedly--AVAUW (ratio of avionics weight to airframe unit weight) and EWAUW (ratio of empty weight minus airframe unit to airframe unit weight). Unfortunately, they generally tend to exacerbate the size variable exponent magnitude problem. Furthermore, the magnitude of the variable EWAUW shows a fair amount of variability--from .305 in M34 to .742 in M28. On the other hand, the variable AVAUW shows relatively little variation across alternative equations--from .177 in M39 to .257 in M27.

(b) The magnitude of the weapon system designator (WSDV) in Equations M41, M42, and M43 seems somewhat large. These equations indicate that a weapon system will incur 75 to 90 percent greater material costs than a gun platform. On the other hand, a reinspection of Fig. 11 suggests that if the full fighter sample is to be utilized, then the magnitude of the weapon system/gun platform difference may not be all that unreasonable.

4. The fighter technology index was not found to be significant at the 5 percent level in the required equation form (size/performance/technology index).

REPRESENTATIVE CERS

Airframe Unit Weight and Speed

No acceptable estimating relationships containing this size/performance variable combination were identified (i.e., the magnitude of all size variable exponents was greater than 1).

Airframe Unit Weight and Specific Power

No acceptable estimating relationships containing this size/performance variable combination were identified (i.e., the magnitude of all size variable exponents was greater than 1).

Airframe Unit Weight and Climb Rate

No acceptable estimating relationships containing this size/performance variable combination were identified (i.e., the magnitude of all size variable exponents was greater than 1).

Airframe Unit Weight and Composite Performance Index

No acceptable estimating relationships containing this size/performance variable combination were identified (i.e., the magnitude of all size variable exponents was greater than 1).

Single Best Estimating Relationship

Based on a summary examination of all 43 manufacturing material cost equations, the list of candidate estimating relationships has been narrowed to one--M41. It is the only equation with a size variable exponent less than 1 (albeit just barely).

$$\text{M41 MATL}_{100} = 5.68\ \underset{(.003)}{\text{AUW}^{.999}}\ \underset{(.011)}{\text{WSDV}^{.935}}$$

R^2	SEE	F	N	RP
.82	.36	27	15	Cur: Under

Post-1960 Sample

$$MATL_{100} = 127\ AUW^{.766}$$

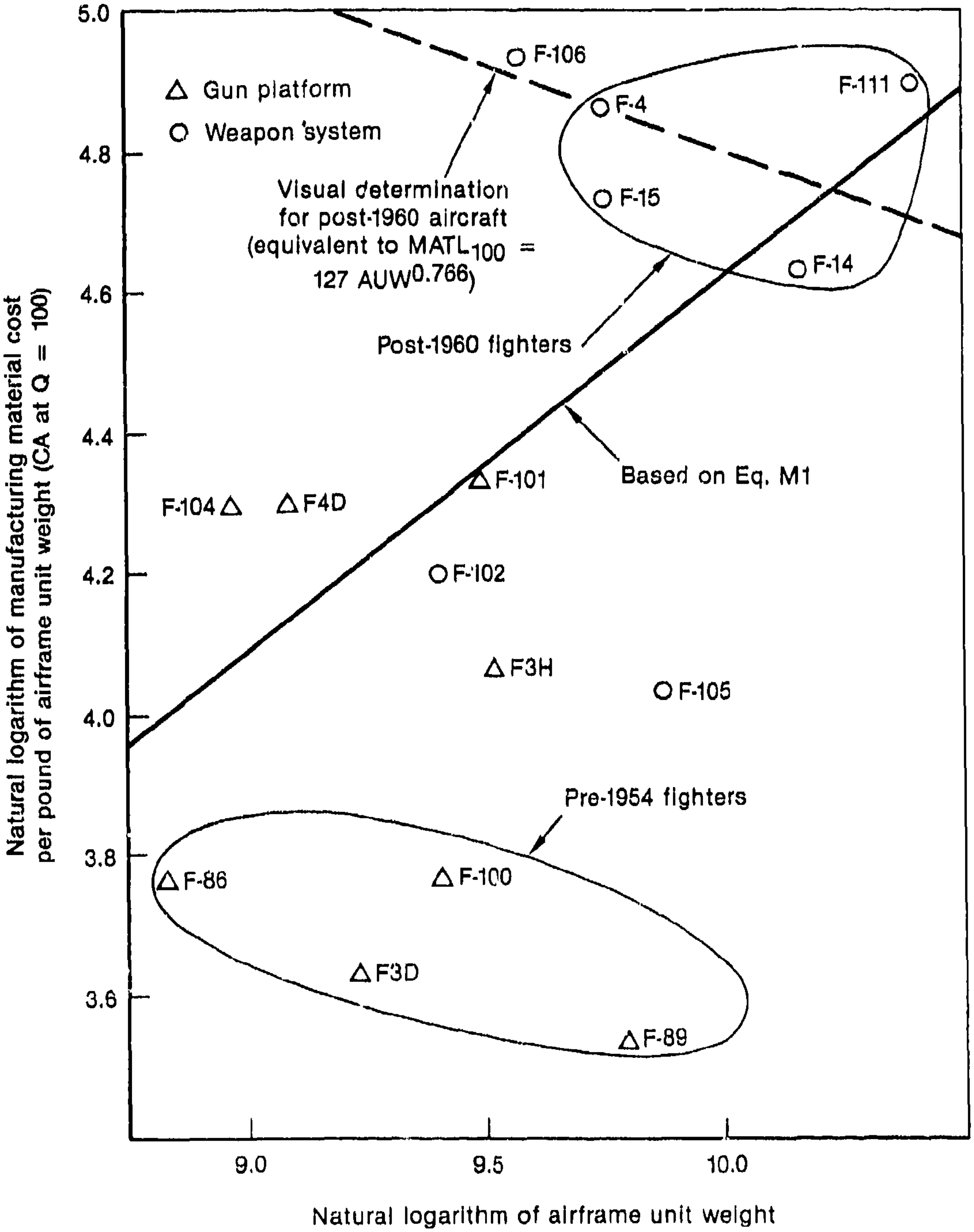

Fig. 11—Manufacturing material cost per pound as a function
of airframe unit weight

Table 9

MANUFACTURING MATERIAL COST ESTIMATING RELATIONSHIPS

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg.	Comments
	SIZE										
M1	$MATL_{100} = .0556\ AUW^{1.52}$ (.000)	.72	.43	33	15	+34	+8	-7	+23	18	EXP MAG:AUW RP:CUR:UNDER IO:F-89
M2	$MATL_{100} = .00352\ EW^{1.73}$ (.000)	.80	.36	52	15	+26	+7	-3	+20	14	EXP MAG:EW RP:CUR:UNDER IO:F-89, F-104
M3	$MATL_{100} = .0204\ WTAREA^{2.06}$ (.001)	.67	.47	24	14	+33	+50	-23	-14	30	EXP MAG:WTAREA IO:F3D, F-104, F-111
	SIZE/PERFORMANCE										
M4	$MATL_{100} = .00517\ AUW^{1.01}\ SP^{1.06}$ (.000) (.001)	.89	.28	46	15	+17	+15	-16	-3	13	EXP MAG:AUW EXP MAG:SP IO:F-89, F-104
M5	$MATL_{100} = 1.32\ AUW^{1.14}\ SPCLS^{.624}$ (.000) (.006)	.84	.34	31	15	+21	+15	-8	+10	14	EXP MAG:AUW RP:CUR:UNDER IO:F4D, F-89
M6	$MATL_{100} = 1.09\ AUW^{1.18}\ SPPWR^{.539}$ (.000) (.001)	.88	.29	44	15	+20	+25	-13	-20	20	EXP MAG:AUW IO:F-89, F-111
M7	$MATL_{100} = .00989\ AUW^{1.37}\ CLIMB^{.314}$ (.000) (.017)	.81	.37	25	15	+24	+34	-20	-1	20	EXP MAG:AUW IO:F-89, F-111

Table 9 (continued)

Eq. No.	Equation	R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg	Comments
		Statistics				Relative Deviations (%)					
M8	$MATL_{100} = (7.06 \times 10^{-5})\ \underset{(.000)}{AUW^{1.18}}\ \underset{(.004)}{ENERGY^{.877}}$	.90	.27	51	14	+22	+3	-21	-14	15	EXP MAG:AUW IO:F-104
M9	$MATL_{100} = .0260\ \underset{(.000)}{AUW^{1.08}}\ \underset{(.001)}{PFFD^{.936}}$	.87	.30	40	15	+29	+20	-35	-40	31	EXP MAG:AUW IO:F-89,F-111,F-15
M10	$MATL_{100} = .298\ \underset{(.000)}{AUW^{1.39}}\ \underset{(.006)}{THWT^{.830}}$	.84	.34	31	15	+26	+29	-10	-22	22	EXP MAG:AUW IO:F-89,F-111
M11	$MATL_{100} = .000785\ \underset{(.000)}{EW^{1.22}}\ \underset{(.000)}{SP^{.963}}$	.94	.21	89	15	+12	+13	-12	-3	10	EXP MAG:EW
M12	$MATL_{100} = .0986\ \underset{(.000)}{EW^{1.35}}\ \underset{(.002)}{SPCLS^{.574}}$	.90	.26	54	15	+15	+13	-5	+8	10	EXP MAG:EW RP:CUR:UNDER
M13	$MATL_{100} = .101\ \underset{(.000)}{EW^{1.37}}\ \underset{(.001)}{SPPWR^{.462}}$	.91	.25	62	15	+15	+23	-8	-16	16	EXP MAG:EW IO:F-111
M14	$MATL_{100} = .00123\ \underset{(.000)}{EW^{1.57}}\ \underset{(.019)}{CLIMB^{.264}}$	.86	.31	38	15	+18	+30	-13	0	15	EXP MAG:EW RP:CUR:UNDER IO:F-111
M15	$MATL_{100} = (1.10 \times 10^{-5})\ \underset{(.000)}{EW^{1.33}}\ \underset{(.000)}{ENERGY^{.861}}$	.95	.19	103	14	+16	+4	-15	-15	12	EXP MAG:EW

Table 9 (continued)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg	Comments
M16	$MATL_{100} = .00376\ EW^{1.28}_{(.000)}\ PFFD^{.824}_{(.001)}$	.91	.25	62	15	+23	+18	-27	-33	25	EXP MAG:EW IO:F-111,F-15
M17	$MATL_{100} = .0235\ EW^{1.57}_{(.000)}\ THWT^{.612}_{(.020)}$	.86	.31	37	15	+20	+25	-4	-11	15	EXP MAG:EW IO:F-104,F-111
M18	$MATL_{100} = .000812\ WTAREA^{1.38}_{(.000)}\ SP^{1.22}_{(.000)}$	.90	.28	48	14	+16	+42	-30	-38	32	EXP MAG:WTAREA IO:F-104,F-111
M19	$MATL_{100} = .647\ WTAREA^{1.53}_{(.001)}\ SPCLS^{.720}_{(.006)}$	.82	.36	25	14	+20	+46	-20	-23	27	EXP MAG:WTAREA IO:F3D,F-111
M20	$MATL_{100} = .596\ WTAREA^{1.57}_{(.000)}\ SPPWR^{.571}_{(.004)}$	.83	.35	28	14	+21	+54	-24	-64	41	EXP MAG:WTAREA IO:F-111,F-15
M21	$MATL_{100} = .00478\ WTAREA^{1.86}_{(.000)}\ CLIMB^{.297}_{(.045)}$	.75	.43	16	14	+25	+62	-34	-42	41	EXP MAG:WTAREA IO:F-3D,F-104, F-111
M22	$MATL_{100} = (2.72 \times 10^{-6})\ WTAREA^{1.43}_{(.000)}\ ENERGY^{1.20}_{(.000)}$	.89	.28	45	14	+21	+38	-32	-64	39	EXP MAG:WTAREA IO:F3D,F-111,F-15
M23	$MATL_{100} = .0182\ WTAREA^{1.34}_{(.004)}\ PFFD^{1.04}_{(.008)}$	.81	.38	23	14	+30	+50	-45	-89	54	EXP MAG:WTAREA IO:F3D,F-111,F-15

Table 9 (continued)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg	Comments
	SIZE/PERFORMANCE/CONSTRUCTION/PROGRAM										
M24	$MATL_{100} = .00122\ \underset{(.000)}{AUW^{1.29}}\ \underset{(.000)}{SP^{.956}}\ \underset{(.001)}{EWAUW^{.736}}$	.95	.19	77	15	+5	+16	-8	-7	9	EXP MAG:AUW 10:F-101
M25	$MATL_{100} = .00707\ \underset{(.000)}{AUW^{1.17}}\ \underset{(.002)}{SP^{.877}}\ \underset{(.013)}{AVAUW^{.259}}$	.94	.22	50	14	+17	+11	-26	+1	14	EXP MAG:AUW 10:F-100
M26	$MATL_{100} = .174\ \underset{(.000)}{AUW^{1.42}}\ \underset{(.002)}{SPPWR^{.446}}\ \underset{(.021)}{EWAUW^{.580}}$	.92	.25	42	15	+12	+23	-7	-18	15	EXP MAG:AUW 10:F-111
M27	$MATL_{100} = .558\ \underset{(.000)}{AUW^{1.32}}\ \underset{(.001)}{SPPWR^{.446}}\ \underset{(.009)}{AVAUW^{.267}}$	.94	.22	55	14	+19	+19	-25	-13	19	EXP MAG:AUW 10:F-111
M28	$MATL_{100} = .00256\ \underset{(.000)}{AUW^{1.62}}\ \underset{(.024)}{CLIMB^{.253}}\ \underset{(.016)}{EWAUW^{.742}}$	.88	.31	26	15	+13	+30	-10	-3	12	EXP MAG:AUW 10:F-104,F-111
M29	$MATL_{100} = .00890\ \underset{(.000)}{AUW^{1.50}}\ \underset{(.011)}{CLIMB^{.269}}\ \underset{(.015)}{AVAUW^{.294}}$	.92	.26	36	14	+21	+26	-36	0	21	EXP MAG:AUW 10:F-111
M30	$MATL_{100} = .0000152\ \underset{(.000)}{AUW^{1.35}}\ \underset{(.000)}{ENERGY^{.905}}\ \underset{(.002)}{EWAUW^{.697}}$	.96	.18	79	14	+10	+7	-11	-21	12	EXP MAG:AUW 10:F-101
M31	$MATL_{100} = .000121\ \underset{(.000)}{AUW^{1.23}}\ \underset{(.003)}{ENERGY^{.828}}\ \underset{(.026)}{AVAUW^{.224}}$	.93	.23	48	14	+21	+4	-27	-10	16	EXP MAG:AUW 10:F-100

Table 9 (continued)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg	Comments
M32	$MATL_{100} = .00675\ \underset{(.000)}{AUW^{1.35}}\ \underset{(.002)}{PFFD^{.786}}\ \underset{(.012)}{EWAUW^{.646}}$	.92	.25	42	15	+19	+19	-23	-35	24	EXP MAG:AUW IO:F-15
M33	$MATL_{100} = .0279\ \underset{(.000)}{AUW^{1.25}}\ \underset{(.015)}{PFFD^{.723}}\ \underset{(.036)}{AVAUW^{.239}}$	.91	.27	34	14	+27	+14	-41	-24	26	EXP MAG:AUW
M34	$MATL_{100} = .000592\ \underset{(.000)}{EW^{1.27}}\ \underset{(.000)}{SP^{.968}}\ \underset{(.051)}{EWAUW^{.305}}$	.95	.19	71	15	+6	+16	-7	-6	9	EXP MAG:EW IO:F-101 VAR SIG:EWAUW
M35	$MATL_{100} = .00115\ \underset{(.000)}{EW^{1.29}}\ \underset{(.000)}{SP^{.878}}\ \underset{(.005)}{AVAUW^{.215}}$	.97	.15	110	14	+11	+13	-18	-1	11	EXP MAG:EW
M36	$MATL_{100} = .0806\ \underset{(.000)}{EW^{1.45}}\ \underset{(.002)}{SPPWR^{.402}}\ \underset{(.018)}{AVAUW^{.214}}$	.95	.20	64	14	+14	+21	-14	-11	15	EXP MAG:EW IO:F-104,F-111
M37	$MATL_{100} = .656\ \underset{(.000)}{EW^{1.17}}\ \underset{(.007)}{SPPWR^{.355}}\ \underset{(.044)}{WSDV^{.478}}$	.93	.23	51	15	+10	+24	-8	-17	15	EXP MAG:EW MCOL:r(WSDV) > .7 IO:F-111
M38	$MATL_{100} = .00158\ \underset{(.000)}{EW^{1.63}}\ \underset{(.015)}{CLIMB^{.236}}\ \underset{(.029)}{AVAUW^{.231}}$	.93	.24	43	14	+14	+27	-22	+1	16	EXP MAG:EW IO:F-104,F-111
M39	$MATL_{100} = .0000168\ \underset{(.000)}{EW^{1.35}}\ \underset{(.000)}{ENERGY^{.843}}\ \underset{(.014)}{AVAUW^{.177}}$	.97	.16	106	14	+15	+6	-19	-13	13	EXP MAG:EW IO:F-100

Table 9 (continued)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg	Comments
M40	$MATL_{100} = .00464\ \underset{(.000)}{EW^{1.37}}\ \underset{(.007)}{PFFD^{.707}}\ \underset{(.041)}{AVAUW^{.192}}$	.94	.23	50	14	+21	+17	-30	-25	23	EXP MAG:EW IO:F-104, F-15
	SIZE/CONSTRUCTION, PROGRAM										
M41	$MATL_{100} = 5.68\ \underset{(.003)}{AUW^{.999}}\ \underset{(.011)}{WSDV^{.935}}$	.82	.36	27	15	+18	+19	-6	+6	12	RP:CUR:UNDER IO:F-89, F-102
M42	$MATL_{100} = .341\ \underset{(.000)}{EW^{1.24}}\ \underset{(.007)}{WSDV^{.824}}$	.88	.29	45	15	+13	+16	-4	+6	10	RP:CUR:UNDER EXP MAG:EW IO:F-89, F-102, F-104
M43	$MATL_{100} = .608\ \underset{(.000)}{AUW^{1.29}}\ \underset{(.004)}{EWAUW^{.817}}\ \underset{(.004)}{WSDV^{.860}}$	.91	.27	36	15	+4	-20	+1	0	6	RP:DIST EXP MAG:AUW MCOL:r(WSDV) > .7 RP:CUR:UNDER IO:F-102, F-104
	SIZE/PERFORMANCE/TECHNOLOGY INDEX										
	None										

VIII. DEVELOPMENT SUPPORT

Development support cost per pound is plotted as a function of airframe unit weight in Fig. 12. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 10.

GENERAL OBSERVATIONS

1. None of the estimating relationships listed in Table 10 comes close to meeting the standard error of estimate goal of 0.18.

2. With one exception (D8), the magnitude of the size variable exponents is greater than 1.7.

3. No equation containing a size/performance variable combination was identified.

4. As adjuncts to airframe unit weight and empty weight, several construction/program variables were determined to be significant at the 5 percent level. However, they provide relatively modest improvement in the equation standard error of estimate. Furthermore, with the exception of the variable AVAUW, most have fairly large exponents.

5. The fighter technology index was not found to be significant at the 5 percent level in the required equation form (size/performance/technology index).

REPRESENTATIVE CERS

Obviously, the equations are missing an important element of development support cost. The missing element could take the form of an explanatory variable such as the quantity of mockups and test articles or it could take the form of a complementarity between development support and another cost element such as engineering.

Previous RAND airframe models used initial engineering hours[1] and airframe unit weight, speed, and the number of test aircraft[2] as

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[1]Ref. 1, p. 21.
[2]Ref. 2, p. 13.

explanatory variables. This study was unable to establish a logical link between development support cost and the number of flight test aircraft. Nonrecurring engineering cost seemed logical, however, since the mockups and test articles that make up development support are required for the airframe design effort. Thus, given the poor results of the regression analysis, development support costs are estimated simply as a percentage of nonrecurring engineering costs. Based on the data provided in Table 11, the following values were obtained:

	Development Support Cost as a Percentage of Unit 1 Engineering Cost
Full fighter sample	108
Post-1960 sample	68

Note that the values shown in Table 11 range from a low of 14 percent (the F-104) to a high of 323 percent (the F-101).

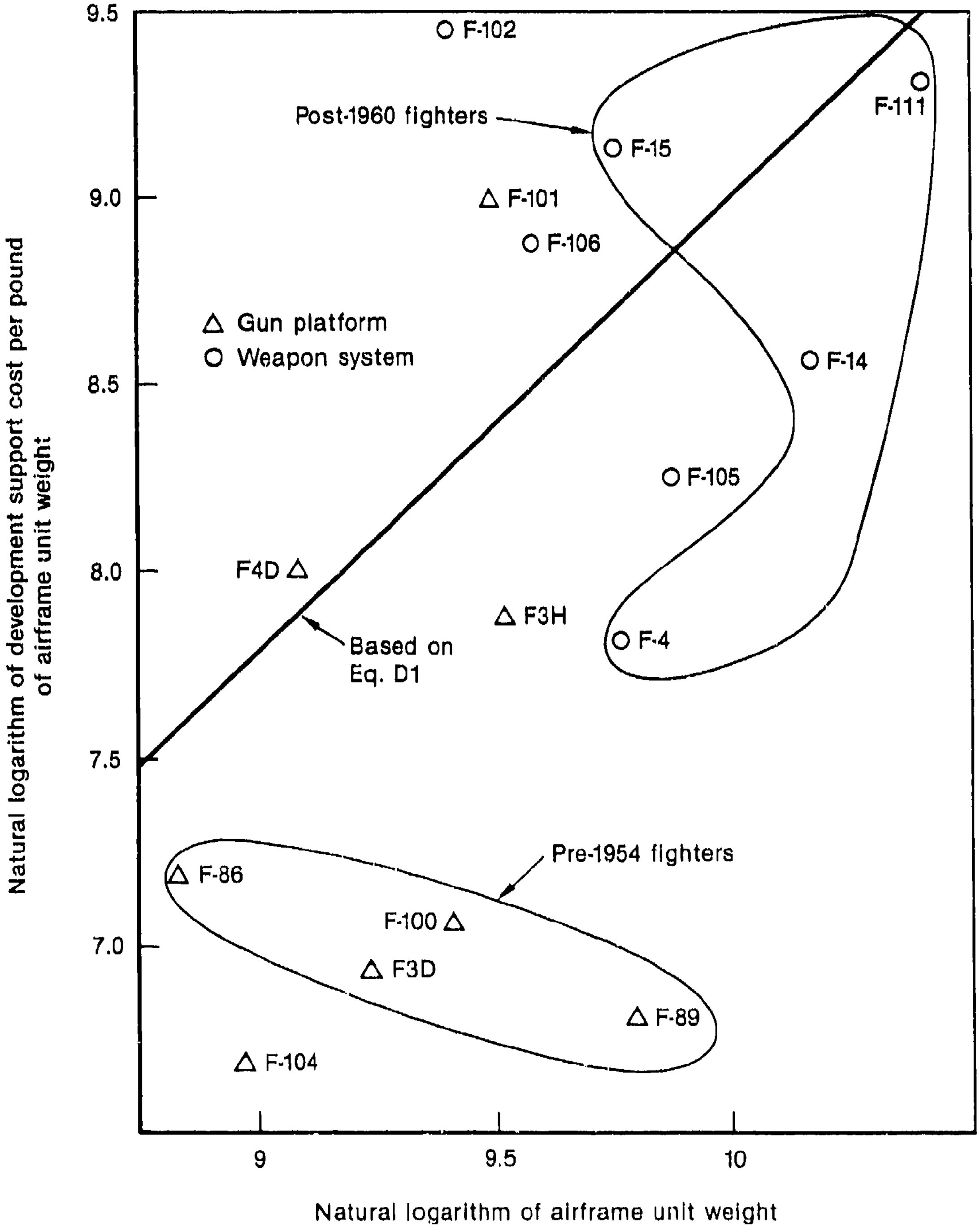

Fig. 12—Development support cost per pound as a function of airframe unit weight

Table 10

DEVELOPMENT SUPPORT COST ESTIMATING RELATIONSHIPS

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg.	Comments
	SIZE										
D1	$DS = .0000598\ \underset{(.001)}{AUW^{2.18}}$	.57	.85	17	15	-129	-13	-81	+36	65	EXP MAG:AUW IO:F-89, F-102
D2	$DS = (4.18 \times 10^{-7})\ \underset{(.000)}{EW^{2.57}}$	.69	.72	29	15	-160	+17	-70	+36	71	EXP MAG:EW IO:F-89, F-102
D3	$DS = (2.28 \times 10^{-7})\ \underset{(.000)}{WTAREA^{3.48}}$	.75	.65	37	14	-110	+53	-147	-15	81	EXP MAG:WTAREA IO:F3D, F-111, F-14
	SIZE/PERFORMANCE										
	None										
	SIZE/CONSTRUCTION, PROGRAM										
D4	$DS = (9.40 \times 10^{-9})\ \underset{(.000)}{AUW^{2.21}}\ \underset{(.021)}{STREFF^{-2.50}}$	.70	.74	14	15	-251	-20	-10	+24	76	EXP MAG:AUW EXP MAG:STREFF IO:F4D, F-89
D5	$DS = .00114\ \underset{(.001)}{AUW^{1.75}}\ \underset{(.009)}{WGTYPE^{1.33}}$	.74	.69	17	15	-68	-57	-177	+54	89	EXP MAG:AUW IO:F-14
D6	$DS = (9.89 \times 10^{-7})\ \underset{(.000)}{AUW^{2.72}}\ \underset{(.010)}{EWAUW^{1.78}}$	.73	.70	16	15	-218	-5	-48	+28	75	EXP MAG:AUW EXP MAG:EWAUW IO:F-105

Table 10 (continued)

Eq. No.	Equation	R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg	Comments
		Statistics				Relative Deviations (%)					
D7	$DS = .0000232\ AUW^{2.41}\ AVAUW^{.567}$ (.000) (.042)	.75	.68	17	14	-149	-27	-131	+35	86	EXP MAG:AUW
D8	$DS = .338\ AUW^{1.20}\ WSDV^{1.76}$ (.035) (.016)	.71	.72	15	15	-229	+14	-71	+11	81	EXP MAG:WSDV IO:F-89,F-101,F-102
D9	$DS = (1.81 \times 10^{-9})\ EW^{2.50}\ STREFF^{-1.83}$ (.000) (.045)	.76	.66	19	15	-256	-16	-14	+26	78	EXP MAG:EW EXP MAG:STREFF IO:F-89,F-4
D10	$DS = .0000172\ EW^{2.11}\ WGTYPE^{1.09}$ (.000) (.016)	.79	.61	23	15	-97	-48	-139	+50	84	EXP MAG:EW IO:F-102,F-14
D11	$DS = (4.87 \times 10^{-7})\ EW^{2.67}\ AVAUW^{.476}$ (.000) (.046)	.81	.59	24	14	-179	-19	-98	+35	83	EXP MAG:EW IO:F-102
D12	$DS = .00128\ EW^{1.71}\ WSDV^{1.46}$ (.005) (.018)	.79	.62	22	15	-235	+3	-71	+15	81	EXP MAG:EW IO:F-10[illegible], F-102
D13	$DS = .00354\ AUW^{1.79}\ EWAUW^{1.65}\ WSDV^{1.60}$ (.002) (.005) (.007)	.85	.55	20	15	-326	+19	-41	+4	98	MCOL:r(AUW > .7) EXP MAG:AUW EXP MAG:EWAUW EXP MAG:WSDV IO:F-4,F-101
D14	$DS = .00110\ EW^{1.79}\ EWAUW^{1.05}\ WSDV^{1.61}$ (.002) (.026) (.007)	.85	.54	21	15	-321	+20	-40	+6	97	EXP MAG:EW EXP MAG:WSDV IO:F-4,F-101
	<u>SIZE/PERFORMANCE/TECHNOLOGY INDEX</u>										
	None										

Table 11

DEVELOPMENT SUPPORT COST AS A PERCENTAGE OF
UNIT 1 ENGINEERING COST

Fighter	Unit 1 Engineering Hours	Unit 1 Engineering Cost ($M)(a)	Development Support Cost ($M)	Development Support as a % of Unit 1 Engineering Cost
F3D	400,000	11.0	10.3	94
F3H	1,300,000	35.8	36.3	102
F4D	1,600,000	44.0	25.3	58
F-86	690,000	19.0	9.0	48
F-89	950,000	26.0	16.6	63
F-4	5,000,000	137.0	42.8	31
F-100	1,450,000	39.9	13.8	34
F-101	1,200,000	33.0	106.7	323
F-102	2,000,000	55.0	157.0	286
F-104	1,670,000	45.9	6.5	14
F-105	4,800,000	132.0	74.4	56
F-106	1,400,000	38.5	103.1	268
F-111	12,500,000	343.8	360.3	105
F-14	8,000,000	233.8	138.3	59
F-15	7,500,000	206.2	161.0	78

(a)At $27.50 per hour.

IX. FLIGHT TEST

Flight test cost per aircraft is plotted as a function of the quantity of flight test aircraft in Fig. 13. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 12.

GENERAL OBSERVATIONS

1. In general, the flight test estimating relationships have relatively high standard errors of estimate compared to the goal of 0.18.

2. The magnitude of the test aircraft exponent is never less than 1. Normally, one would expect that as the number of test aircraft increases, less testing would be required of each aircraft. Unfortunately, this analysis was not able to verify this premise.

3. Equations incorporating specific power and the composite performance index (F5, F8, F10, F13, F16, and F19) do very poorly on the F-15 aircraft.

REPRESENTATIVE CERS

Airframe Unit Weight, Speed, and Test Aircraft

$$F4\ FT = .0000215\ \underset{(.061)}{AUW^{.771}}\ \underset{(.007)}{SP^{1.62}}\ \underset{(.003)}{TESTAC^{1.30}}$$

R^2	SEE	F	N	RP
.80	.59	15	15	None

Airframe Unit Weight, Specific Power, and Test Aircraft

$$F5\ FT = .179\ \underset{(.013)}{AUW^{.940}}\ \underset{(.002)}{SPPWR^{.951}}\ \underset{(.002)}{TESTAC^{1.25}}$$

R^2	SEE	F	N	RP
.85	.52	20	15	None

Airframe Unit Weight, Climb Rate, and Test Aircraft

$$F6\ FT = .0000177\ AUW^{1.27}\ CLIMB^{.601}\ TESTAC^{1.44}$$
$$\quad(.004)\quad(.011)\quad(.002)$$

R^2	SEE	F	N	RP
.79	.61	14	15	None

Airframe Unit Weight, Composite Performance Index, and Test Aircraft

$$F8\ FT = .000313\ AUW^{.807}\ PFFD^{1.54}\ TESTAC^{1.21}$$
$$\quad(.051)\quad(.007)\quad(.006)$$

R^2	SEE	F	N	RP
.80	.59	15	15	None

Single Best Estimating Relationship

Based on a summary examination of all 21 flight test cost equations, the list of candidate estimating relationships has been narrowed to F5, F9, F10, F11, and F12. Equation F-10 has the lowest standard error of estimate while F12 places the least emphasis on the test aircraft variable. Equation F10 is selected:

$$F10\ FT = .00623\ EW^{1.24}\ SPPWR^{.846}\ TESTAC^{1.25}$$
$$\quad(.002)(.002)\quad(.001)$$

R^2	SEE	F	N	RP
.88	.45	28	15	None

Post-1960 Sample

$$FT = 27100\ TESTAC^{.687}$$

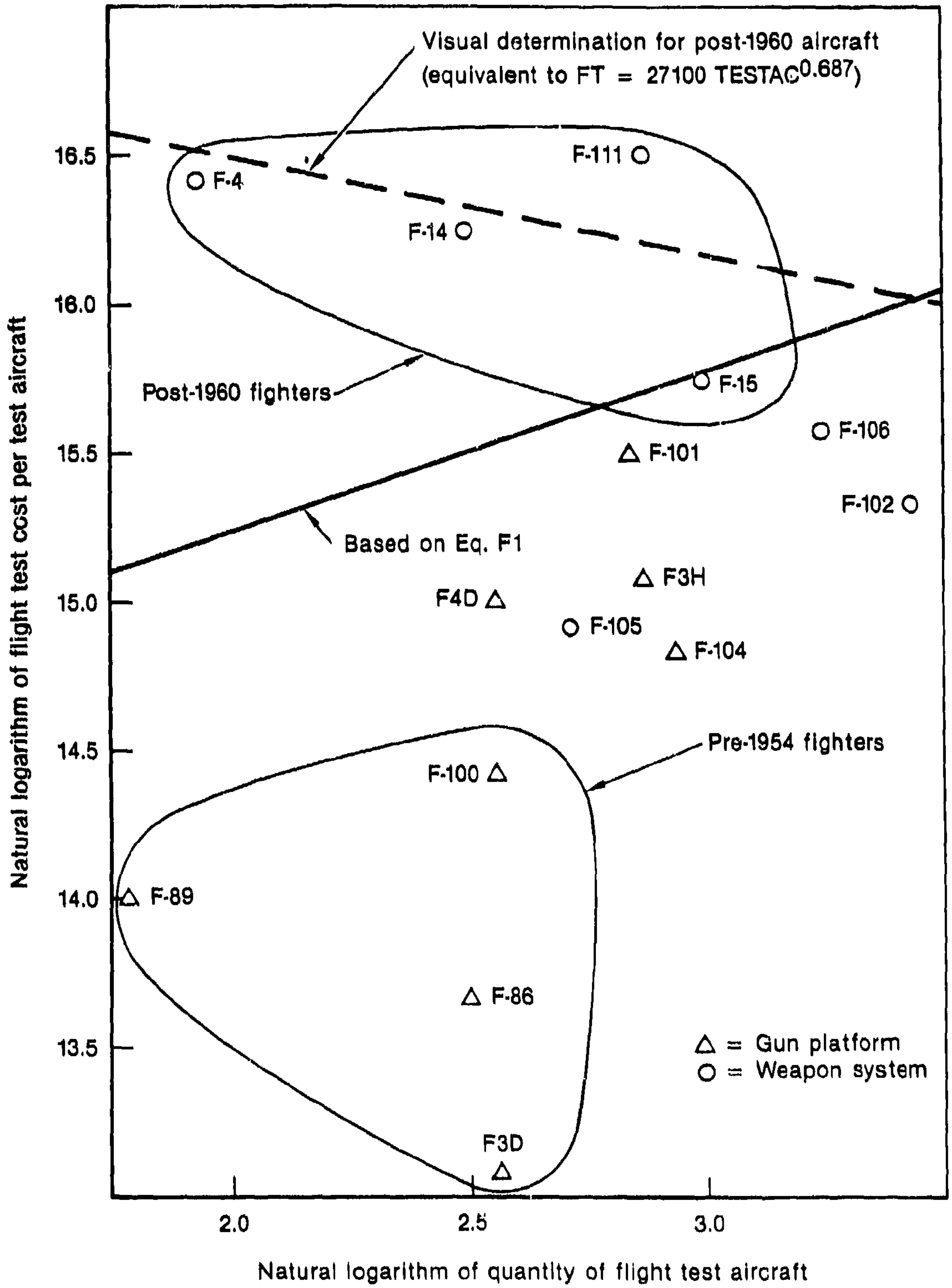

Fig. 13—Flight test cost per test aircraft as a function of the quantity of flight test aircraft

Table 12

FLIGHT TEST COST ESTIMATING RELATIONSHIPS

Eq. No.	Equation	Statistics				Relative Deviations (%)					Comments
		R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg.	
	TEST AIRCRAFT										
F1	$FT = 1430\ \underset{(.014)}{TESTAC^{1.53}}$	.32	1.01	6	15	+70	+56	+51	+2	45	RP:CUR:UNDER EXP MAG:TESTAC IO:F3D,F-89,F-4
	SIZE/TEST AIRCRAFT										
F2	$FT = .000229\ \underset{(.003)}{AUW^{1.58}}\ \underset{(.002)}{TESTAC^{1.67}}$	.65	.75	11	15	+71	-37	-2	-14	31	EXP MAG:AUW EXP MAG:TESTAC IO:F-89,F-4
F3	$FT = (5.14 \times 10^{-6})\ \underset{(.000)}{EW^{1.91}}\ \underset{(.001)}{TESTAC^{1.59}}$	.74	.65	17	15	+66	-42	-1	-14	31	EXP MAG:EW EXP MAG:TESTAC IO:F-89,F-4,F-3D
	SIZE/PERFORMANCE/TEST AIRCRAFT										
F4	$FT = .0000215\ \underset{(.061)}{AUW^{.771}}\ \underset{(.007)}{SP^{1.62}}\ \underset{(.003)}{TESTAC^{1.30}}$	.80	.59	15	15	+48	-7	-18	-54	32	VAR SIG:AUW EXP MAG:TESTAC IO:F-4,
F5	$FT = .179\ \underset{(.013)}{AUW^{.940}}\ \underset{(.002)}{SPPWR^{.951}}\ \underset{(.002)}{TESTAC^{1.25}}$	.85	.52	20	15	+49	+19	-13	-107	47	EXP MAG:TESTAC IO:F-4
F6	$FT = .0000177\ \underset{(.004)}{AUW^{1.27}}\ \underset{(.011)}{CLIMB^{.601}}\ \underset{(.002)}{TESTAC^{1.44}}$	.79	.61	14	15	+58	+35	-25	-70	47	EXP MAG:TESTAC IO:F-89,F-4,F-111

Table 12 (continued)

Eq. No.	Equation	Statistics: R^2	SEE	F	N	Relative Deviations (%): F-4	F-111	F-14	F-15	Abs Avg	Comments
F7	$FT = (5.27 \times 10^{-8}) \underset{(.032)}{AUW^{1.01}} \underset{(.026)}{ENERGY^{1.35}} \underset{(.018)}{TESTAC^{1.11}}$	.76	.60	10	14	+44	-28	-33	-73	44	EXP MAG:TESTAC 10:F3D,F-4
F8	$FT = .000313 \underset{(.051)}{AUW^{.807}} \underset{(.007)}{PFFD^{1.54}} \underset{(.006)}{TESTAC^{1.21}}$	.80	.59	15	15	+56	+6	-55	-156	68	VAR SIG:AUW EXP MAG:TESTAC 10:F-4,F-15
F9	$FT = .00000130 \underset{(.010)}{EW^{1.17}} \underset{(.007)}{SP^{1.39}} \underset{(.001)}{TESTAC^{1.31}}$	.85	.51	21	15	+48	-20	-19	-48	34	EXP MAG:TESTAC 10:F-4
F10	$FT = .00623 \underset{(.002)}{EW^{1.24}} \underset{(.002)}{SPPWR^{.846}} \underset{(.001)}{TESTAC^{1.25}}$	.88	.45	28	15	+47	+11	-12	-93	41	EXP MAG:TESTAC 10:F-4
F11	$FT = (9.84 \times 10^{-7}) \underset{(.001)}{EW^{1.57}} \underset{(.009)}{CLIMB^{.539}} \underset{(.001)}{TESTAC^{1.40}}$	.85	.52	20	15	+54	+27	-21	-62	41	EXP MAG:EW EXP MAG:TESTAC 10:F-89,F-4,F-111
F12	$FT = (6.92 \times 10^{-9}) \underset{(.005)}{EW^{1.36}} \underset{(.020)}{ENERGY^{1.18}} \underset{(.008)}{TESTAC^{1.10}}$	.83	.51	16	14	+42	-36	-31	-63	43	EXP MAG:TESTAC 10:F-4,F-102,F-3D
F13	$FT = .0000159 \underset{(.010)}{EW^{1.18}} \underset{(.009)}{PFFD^{1.32}} \underset{(.002)}{TESTAC^{1.23}}$	.85	.52	20	15	+54	-6	-48	-128	59	EXP MAG:TESTAC 10:F-4,F-15

Table 12 (continued)

Eq. No.	Equation	R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg	Comments
	PERFORMANCE/TEST AIRCRAFT										
F14	$FT = .00123\ SP^{2.18}_{(.000)}\ TESTAC^{1.13}_{(.008)}$	.75	.64	18	15	+37	+32	+2	-62	33	EXP MAG:TESTAC IO:F-4,F-102
F15	$FT = 1830\ SPCLS^{1.44}_{(.003)}\ TESTAC^{1.01}_{(.030)}$	.65	.75	11	15	+34	+41	+18	-26	30	EXP MAG:TESTAC RP:CUR:UNDER IO:F3H,F-4
F16	$FT = 2290\ SPPWR^{1.26}_{(.000)}\ TESTAC^{1.05}_{(.012)}$	.75	.63	18	15	+38	+60	+16	-134	62	EXP MAG:TESTAC IO:F-4
F17	$FT = .744\ CLIMB^{.811}_{(.008)}\ TESTAC^{1.26}_{(.015)}$	.59	.82	9	15	+50	+78	+21	-77	56	EXP MAG:TESTAC IO:F3D,F-4,F-111
F18	$FT = (1.08 \times 10^{-7})\ ENERGY^{2.14}_{(.001)}\ TESTAC^{1.08}_{(.031)}$	.65	.69	10	14	+40	+23	0	-120	46	EXP MAG:ENERGY EXP MAG:TESTAC IO:F3D,F-4,F-102
F19	$FT = .0674\ PFFD^{2.10}_{(.000)}\ TESTAC^{1.00}_{(.016)}$	.74	.64	17	15	+49	+44	-40	-224	89	EXP MAG:PFFD IO:F-4,F-15
F20	$FT = 580\ SUSLD^{1.28}_{(.048)}\ TESTAC^{1.36}_{(.019)}$	.46	.93	5	15	+66	+74	+38	-59	59	EXP MAG:TESTAC RP:CUR:UNDER IO:F3D,F-4,F-111
F21	$FT = 11100\ THWT^{2.05}_{(.004)}\ TESTAC^{1.12}_{(.022)}$	.62	.78	10	15	+50	+75	+38	-158	80	EXP MAG:THWT EXP MAG:TESTAC IO:F-4,F-111

X. QUALITY CONTROL

Quality control hours per pound are plotted as a function of airframe unit weight in Fig. 14. The data, which do not fit any obvious patterns, are available for only eight aircraft. Consequently, regression analysis does not seem appropriate.[1] However, since quality control is closely related to direct manufacturing labor, it can be estimated as a percentage of same. The ratio of cumulative quality control hours to cumulative manufacturing labor hours is as follows:

Aircraft	Ratio (at Q = 100)
F-4	.076
F-100	.123
F-102	.069
F-105	.101
F-106	.172
F-111	.162
F-14	.116
F-15	.181
Average, all fighters	.125
Average, post-1960 fighters	.134

[1] One-variable estimating relationships containing the three size characteristics were determined, though, and are presented in Table 13.

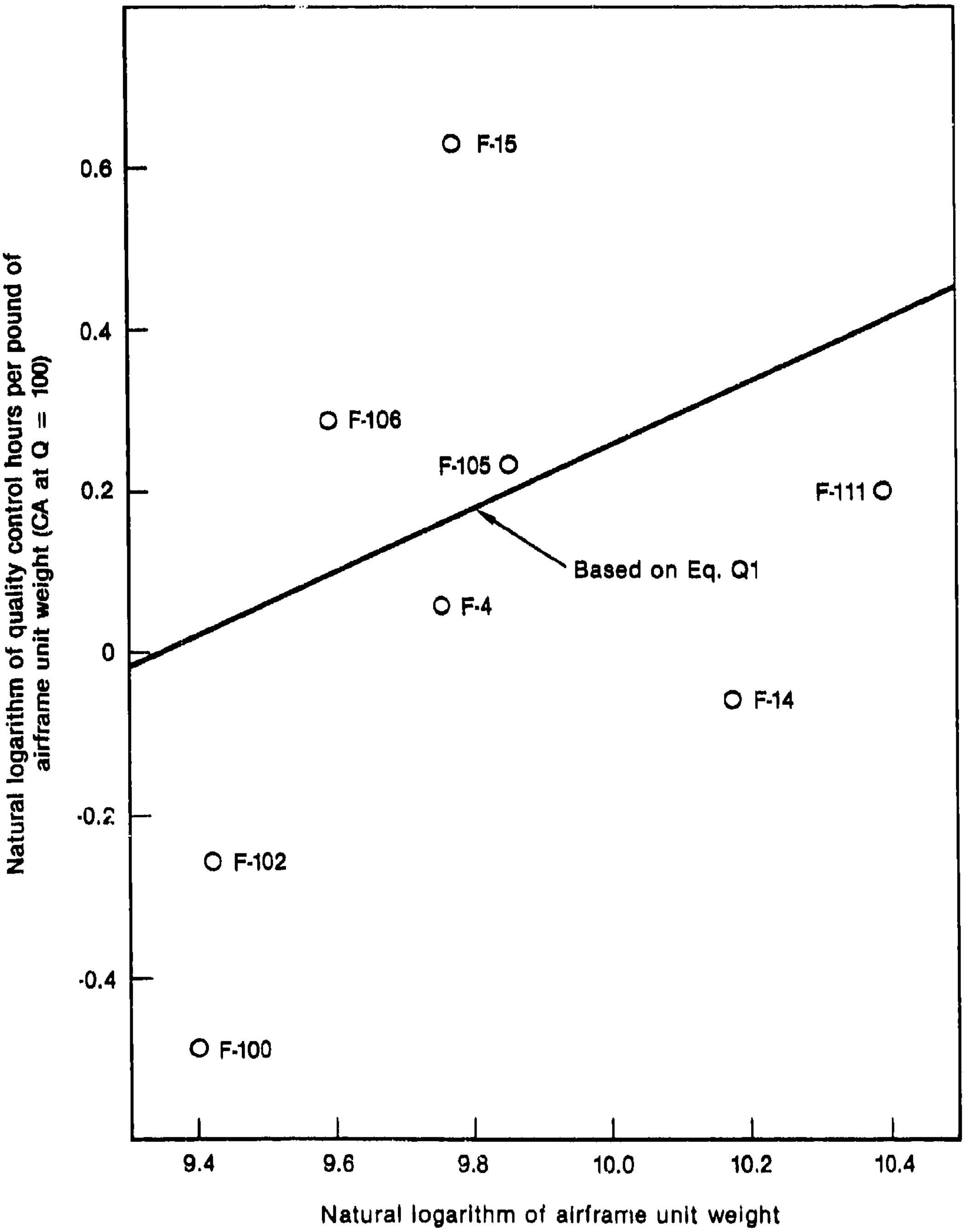

Fig. 14—Quality control hours per pound as a function of airframe unit weight

Table 13

QUALITY CONTROL HOUR ESTIMATING RELATIONSHIPS

Eq. No.	Equation	Statistics				Relative Deviations (%)					Comments
		R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg.	
	SIZE										
Q1	$QC_{100} = .00288\ \underset{(.005)}{AUW^{1.38}}$	.70	.35	14	8	-8	-18	-39	+40	26	EXP MAG:AUW 10:F-100,F-111, F-14,F-15
Q2	$QC_{100} = .000258\ \underset{(.005)}{EW^{1.56}}$	.69	.35	14	8	-21	-20	-36	+37	28	EXP MAG:EW 10:F-100,F-111, F-14,F-15
Q1	$QC_{100} = .00519\ \underset{(.017)}{WTAREA^{1.97}}$	.55	.42	7	8	-7	+32	-63	+12	28	EXP MAG:WTAREA 10:F-100,F-102, F-105,F-111,F-14

XI. TOTAL PROGRAM COST

Total program cost per pound is plotted as a function of airframe unit weight in Fig. 15. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 14.

GENERAL OBSERVATIONS

1. Many cost analysts believe greater accuracy can be obtained by estimating at the total program level rather than the individual cost element level, and that this approach eliminates definitional problems and minimizes the effects of cost element complementarities. It does have one serious drawback, however: It is based on labor rates for a given year. Calculation of a composite adjustment factor to update the base year costs requires that escalation rates be determined for each cost element and then weighted by the appropriate cost element proportion of total cost. Since there is evidence to suggest that the individual cost elements increase at different annual rates[1] and since the proportion of total cost held by each cost element varies with quantity,[2] the task is not a trivial one.

2. Of the 65 equations, approximately 80 percent have size variables with exponents greater than 1.

3. With respect to the construction/program variables:

   (a) The ratio of wing area to wetted area has a counter-intuitive sign each time it appears.

   (b) The variable PRGDV suggests that a prototype development approach would incur only 60 to 70 percent of the costs of a concurrent development approach.

---
[1]See Sec. XIV.
[2]See Sec. II.

(c) The two variables that characterize what gets stuffed into an aircraft, AVAUW and EWAUW, appear fairly frequently. The minimum (.214 in P59) and maximum (.319 in P38) AVAUW exponent values indicate that a 50 percent increase in the ratio of avionics weight to airframe unit weight will result in a 9 to 14 percent increase in total program costs. The minimum (.494 in P31) and maximum (.656 in P27) EWAUW exponents indicate that a 50 percent increase in the ratio of empty weight minus airframe unit weight to airframe unit weight will result in a 20 to 30 percent increase in total program cost. From the standpoint of credibility, the magnitude of the change in total program cost resulting from the AVAUW increase seems quite reasonable but the change resulting from the EWAUW increase seems somewhat excessive.

(d) The magnitude of the weapon system designator (WSDV) shows a fair amount of variability depending on the other equation variables. When used in conjunction with a size/performance variable combination, the exponent varies between .550 (P62) and .658 (P58)--a weapon system would cost 45 to 60 percent more than a gun platform. When used in conjunction with only a size variable, the exponent varies between .834 (P65) and .944 (P64)--a weapon system would cost 80 to 90 percent more than a gun platform. These latter values seem fairly large until one looks at the plot (Fig. 15).

(e) The wing type designator (WGTYPE) appears in equations several times. The exponent magnitude suggests that a fighter with a variable sweep wing will incur 25 (P50) to 45 percent (P40) higher program costs than a swept wing fighter. This seems somewhat excessive. Additionally, an equation using this variable could pose potential problems if used for an advanced design fighter incorporating a new or as yet undesignated wing concept such as forward sweep or variable incidence: What numerical value should be assigned to the new concept?

4. The fighter technology index was not found to be significant at the 5 percent level in the required equation form (size/performance/technology index).

REPRESENTATIVE CERS

Airframe Unit Weight and Speed

Candidate estimating relationships are P4, P27, P28, P29, and P30. Equations P27, P28, and P29 are eliminated for reasons of size variable exponent magnitude. Of the two remaining estimating relationships, P30 is eliminated because it contains the wing type designator, which could prove troublesome for advanced wing concepts. This leaves P4:

$$P4\ PROG_{100} = .450\ \underset{(.001)}{AUW^{.951}}\ \underset{(.007)}{SP^{.800}}$$

R^2	SEE	F	N	RP
.82	.31	28	15	None

Airframe Unit Weight and Specific Power

Candidate estimating relationships are P6, P31, P32, P33, P34, P35, and P36. Equations P6, P31, P32, and P33 are eliminated for reasons of size variable exponent magnitude. Equation P34 is eliminated because it contains the wing type designator, which could prove troublesome for advanced wing concepts. Equation P36 is eliminated because the magnitude of the program type designator (PRGDV) seems excessive. This leaves P35.

$$P35\ PROG_{100} = 290\ \underset{(.001)}{AUW^{.805}}\ \underset{(.012)}{SPPWR^{.349}}\ \underset{(.041)}{WSDV^{.557}}$$

R^2	SEE	F	N	RP
.90	.25	32	15	None

Airframe Unit Weight and Climb Rate

No acceptable estimating relationships containing this size/performance variable combination were identified. The magnitude of all size variable exponents in candidate CERs (P7, P37, P38, P39, and P40) was greater than 1.

Airframe Unit Weight and Composite Performance Index

Candidate estimating relationships are P9, P44, P45, P46, and P47. Equations P44 and P45 are eliminated for reasons of size variable exponent magnitude. Equation P46 is eliminated because it contains the wing type designator, which could prove troublesome for advanced wing concepts. Equation P47 is eliminated because the magnitude of the program type designator (PRGDV) seems excessive. This leaves P9:

$$\text{P9}\quad PROG_{100} = 1.39\ \underset{(.000)}{AUW^{.951}}\ \underset{(.003)}{PFFD^{.810}}$$

R^2	SEE	F	N	RP
.95	.29	33	15	None

Single Best Estimating Relationships

Based on a summary examination of all 65 total program cost equations, the list of candidate estimating relationships has been narrowed to P4, P9, P35, P54, P62, and P64. Of these, P35, P54, and P62 have the lowest standard errors of estimate--between .20 and .25. Of these last three, equation P35 is preferred because it provides more reasonable economies of scale with respect to the size variable:

$$\text{P35}\quad PROG_{100} = 290\ \underset{(.000)}{AUW^{.805}}\ \underset{(.012)}{SPPWR^{.349}}\ \underset{(.041)}{WSDV^{.557}}$$

R^2	SEE	F	N	RP
.90	.25	32	15	None

Post-1960 Sample

$$PROG_{100} = 550\ AUW^{.812}$$

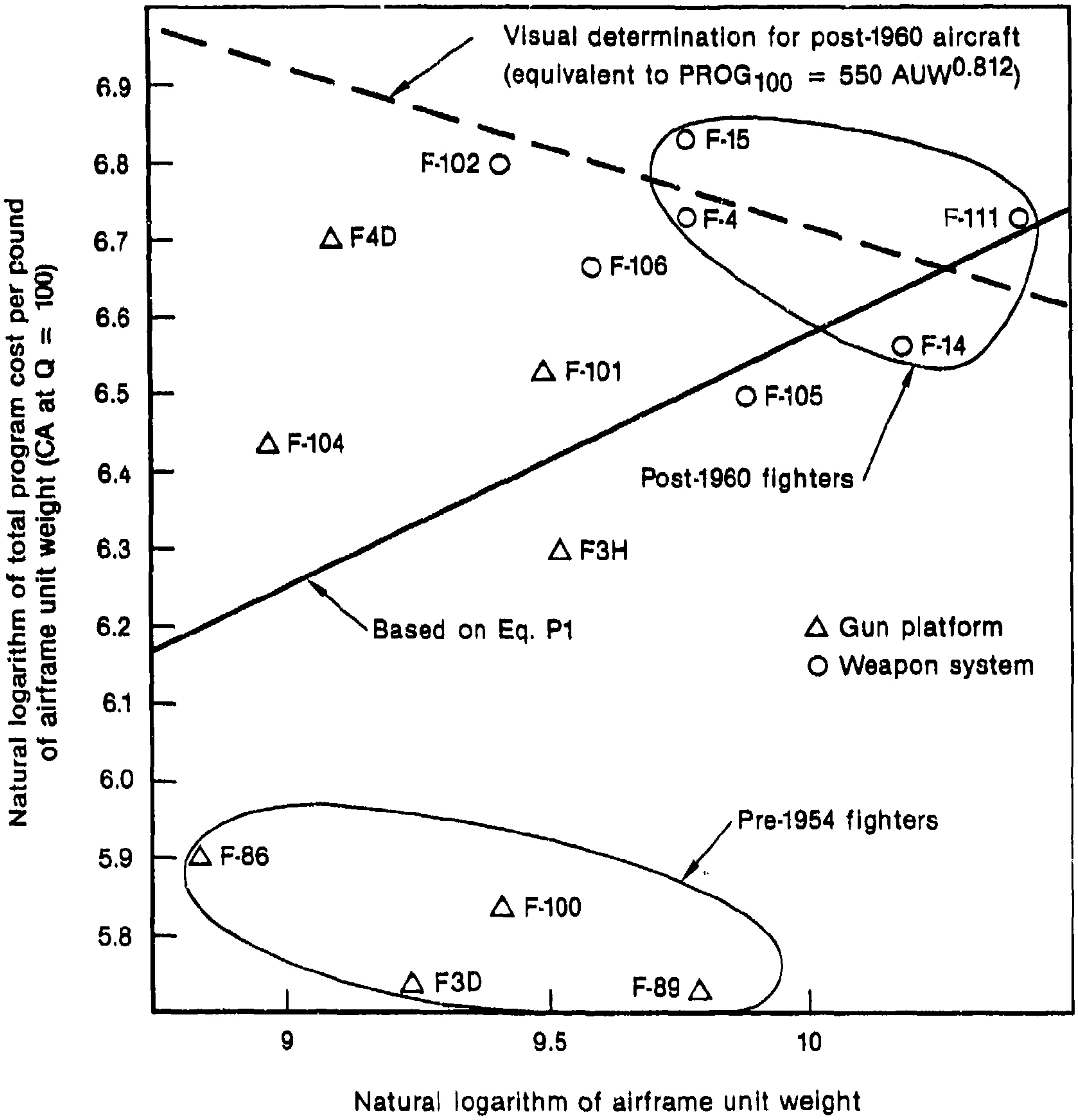

Fig. 15—Total program cost per pound as a function of airframe unit weight

Table 14

TOTAL PROGRAM COST ESTIMATING RELATIONSHIPS

Eq. No.	Equation	Statistics				Relative Deviations (%)					Comments
		R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg	
	SIZE										
P1	$PROG_{100} = 2.67\ \underset{(.000)}{AUW^{1.33}}$	.70	.39	31	15	+18	-3	-14	+26	15	EXP MAG:AUW IO:F3D,F4D,F-86, F-89
P2	$PROG_{100} = .223\ \underset{(.000)}{EW^{1.53}}$	.79	.33	49	15	+9	-4	-11	+23	12	EXP MAG:EW IO:F3D,F-89,F-104
P3	$PROG_{100} = .668\ \underset{(.000)}{WTAREA^{1.88}}$	.70	.40	28	14	+18	+40	-31	-6	24	EXP MAG:WTAREA IO:F-3D,F-104,F-111
	SIZE/PERFORMANCE										
P4	$PROG_{100} = .450\ \underset{(.001)}{AUW^{.951}}\ \underset{(.007)}{SP^{.800}}$	.82	.31	28	15	+2	+2	-23	+7	8	IO:F4D,F-89,F-104
P5	$PROG_{100} = 33.9\ \underset{(.001)}{AUW^{1.03}}\ \underset{(.017)}{SPCLS^{.498}}$	.80	.34	24	15	+5	+3	-16	+15	10	EXP MAG:AUW IO:F4D,F-89
P6	$PROG_{100} = 37.7\ \underset{(.000)}{AUW^{1.03}}\ \underset{(.001)}{SPPWR^{.478}}$	.86	.28	38	15	+3	+14	-21	-11	12	EXP MAG:AUW IO:F-89
P7	$PROG_{100} = .501\ \underset{(.000)}{AUW^{1.19}}\ \underset{(.012)}{CLIMB^{.304}}$	.81	.33	25	15	+6	+25	-28	+4	16	EXP MAG:AUW IO:F-89,F-111

Table 14 (continued)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg	Comments
P8	$PROG_{100} = .0200\ \underset{(.000)}{AUW^{1.10}}\ \underset{(.031)}{ENERGY^{.630}}$	.85	.30	31	14	+6	-10	-28	0	11	EXP MAG:AUW IO:F3D,F-104
P9	$PROG_{100} = 1.39\ \underset{(.000)}{AUW^{.951}}\ \underset{(.003)}{PFFD^{.810}}$	.85	.29	33	15	+12	+8	-40	-25	21	
P10	$PROG_{100} = 2.09\ \underset{(.000)}{AUW^{1.30}}\ \underset{(.033)}{SUSLD^{.537}}$	.78	.35	21	15	+17	+17	-24	+6	16	EXP MAG:AUW IO:F-111
P11	$PROG_{100} = 15.1\ \underset{(.000)}{AUW^{1.20}}\ \underset{(.001)}{THWT^{.858}}$	.85	.28	38	15	+8	+21	-18	-19	16	EXP MAG:AUW IO:F-89,F-111
P12	$PROG_{100} = .0739\ \underset{(.000)}{EW^{1.16}}\ \underset{(.005)}{SP^{.706}}$	.88	.25	45	15	-4	-1	-20	+7	8	EXP MAG:EW
P13	$PROG_{100} = 3.01\ \underset{(.000)}{EW^{1.23}}\ \underset{(.010)}{SPCLS^{.450}}$	.87	.27	40	15	-2	0	-14	+14	8	EXP MAG:EW IO:F4D
P14	$PROG_{100} = 4.25\ \underset{(.000)}{EW^{1.21}}\ \underset{(.002)}{SPPWR^{.407}}$	.90	.24	54	15	-3	+12	-16	-7	10	EXP MAG:EW
P15	$PROG_{100} = .0778\ \underset{(.000)}{EW^{1.37}}\ \underset{(.011)}{CLIMB^{.260}}$	.87	.27	39	15	-1	+21	-22	+4	12	EXP MAG:EW IO:F-111

Table 14 (continued)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg	Comments
P16	$PROG_{100} = .00350\ \underset{(.000)}{EW^{1.25}}\ \underset{(.013)}{ENERGY^{.613}}$	.90	.24	50	14	-1	-9	-22	-1	8	EXP MAG:EW IO:F-102
P17	$PROG_{100} = .233\ \underset{(.000)}{EW^{1.15}}\ \underset{(.003)}{PFFD^{.704}}$	.89	.24	51	15	+6	+6	-34	-20	16	EXP MAG:EW
P18	$PROG_{100} = .233\ \underset{(.000)}{EW^{1.48}}\ \underset{(.038)}{SUSLD^{.439}}$	.84	.30	32	15	+9	+13	-18	+7	12	EXP MAG:EW IO:F-104
P19	$PROG_{100} = 1.74\ \underset{(.000)}{EW^{1.36}}\ \underset{(.005)}{THWT^{.670}}$	.88	.25	45	15	+2	+18	-12	-10	10	EXP MAG:EW IO:F-111
P20	$PROG_{100} = .0614\ \underset{(.000)}{WTAREA^{1.37}}\ \underset{(.002)}{SP^{.912}}$	.86	.29	34	14	+1	+32	-40	-24	24	EXP MAG:WTAREA IO:F3D
P21	$PROG_{100} = 9.87\ \underset{(.001)}{WTAREA^{1.46}}\ \underset{(.012)}{SPCLS^{.559}}$	.82	.33	24	14	+5	+35	-30	-13	21	EXP MAG:WTAREA IO:F3D, F4D
P22	$PROG_{100} = 12.4\ \underset{(.000)}{WTAREA^{1.45}}\ \underset{(.003)}{SPPWR^{.493}}$	.86	.29	33	14	+4	+44	-33	-46	32	EXP MAG:WTAREA IO:F3D, F-111, F-15
P23	$PROG_{100} = .166\ \underset{(.000)}{WTAREA^{1.68}}\ \underset{(.025)}{CLIMB^{.285}}$	.79	.35	21	14	+8	+53	-42	-30	33	EXP MAG:WTAREA IO:F3D, F-111

Table 14 (continued)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg	Comments
P24	$PROG_{100} = .000798\ \underset{(.000)}{WTAREA^{1.40}}\ \underset{(.002)}{ENERGY^{.907}}$	.86	.29	34	14	+6	+28	-41	-41	29	EXP MAG:WTAREA IO:F3D,F-14
P25	$PROG_{100} = .614\ \underset{(.002)}{WTAREA^{1.28}}\ \underset{(.011)}{PFFD^{.854}}$	.82	.33	25	14	+14	+39	-52	-61	42	EXP MAG:WTAREA IO:F3D,F-14,F-15
P26	$PROG_{100} = 4.95\ \underset{(.000)}{WTAREA^{1.66}}\ \underset{(.019)}{THWT^{.713}}$	.80	.34	22	14	+11	+51	-29	-49	35	EXP MAG:WTAREA IO:F3D,F-104,F-111, F-15
	<u>SIZE/PERFORMANCE/CONSTRUCTION, PROGRAM</u>										
P27	$PROG_{100} = .124\ \underset{(.000)}{AUW^{1.20}}\ \underset{(.005)}{SP^{.709}}\ \underset{(.011)}{EWAUW^{.656}}$	.89	.25	30	15	-11	+2	-16	+3	8	EXP MAG:AUW
P28	$PROG_{100} = .632\ \underset{(.000)}{AUW^{1.13}}\ \underset{(.023)}{SP^{.603}}\ \underset{(.014)}{AVAUW^{.283}}$	.90	.25	31	14	+2	-3	-35	+10	12	EXP MAG:AUW IO:F3D
P29	$PROG_{100} = .235\ \underset{(.000)}{AUW^{1.16}}\ \underset{(.012)}{SP^{.777}}\ \underset{(.028)}{WGWET^{.792}}$	.89	.27	27	14	-6	-3	-12	+5	6	EXP MAG:AUW EXP SIGN:WGWET MCOL:r(SP) > .7
P30	$PROG_{100} = 2.56\ \underset{(.000)}{AUW^{.939}}\ \underset{(.049)}{SP^{.504}}\ \underset{(.027)}{WGTYPE^{.476}}$	.88	.27	26	15	+16	-14	-42	+22	24	

Table 14 (continued)

Eq. No.	Equation	R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg	Comments
		Statistics				Relative Deviations (%)					
P31	$PROG_{100} = 7.91\ AUW^{1.23}\ SPPWR^{.398}\ EWAUW^{.494}$ (.000) (.004) (.037)	.90	.25	33	15	-6	+12	-15	-9	10	EXP MAG:AUW
P32	$PROG_{100} = 23.9\ AUW^{1.16}\ SPPWR^{.405}\ AVAUW^{.290}$ (.000) (.001) (.003)	.94	.19	57	14	+1	+9	-33	-5	12	EXP MAG:AUW IO:F3D
P33	$PROG_{100} = 14.2\ AUW^{1.23}\ SPPWR^{.419}\ WGWET^{.616}$ (.000) (.004) (.041)	.91	.24	34	14	-2	+7	-13	-8	8	EXP MAG:AUW EXP SIGN:WGWET
P34	$PROG_{100} = 44.8\ AUW^{.986}\ SPPWR^{.343}\ WGTYPE^{.407}$ (.000) (.012) (.032)	.90	.24	33	15	+14	-2	-38	+9	16	
P35	$PROG_{100} = 290\ AUW^{.805}\ SPPWR^{.349}\ WSDV^{.557}$ (.001) (.012) (.041)	.90	.25	32	15	-6	+16	-18	-12	13	MCOL:r(WSDV) > .7 IO:F-102
P36	$PROG_{100} = 473\ AUW^{.795}\ SPPWR^{.311}\ PRGDV^{-.633}$ (.001) (.020) (.025)	.91	.24	35	15	-3	+18	-15	-7	11	MCOL:r(PRGDV) > .7 EXP MAG:PRGDV IO:F4D
P37	$PROG_{100} = .162\ AUW^{1.40}\ CLIMB^{.253}\ EWAUW^{.623}$ (.000) (.016) (.022)	.87	.28	25	15	-5	+22	-19	+2	12	EXP MAG:AUW IO:F-111
P38	$PROG_{100} = .479\ AUW^{1.30}\ CLIMB^{.276}\ AVAUW^{.319}$ (.000) (.003) (.003)	.93	.21	47	14	+2	+19	-44	+4	17	EXP MAG:AUW IO:F3D, F-111, F-14

Table 14 (continued)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg	Comments
P39	$PROG_{100} = .257\ \underset{(.000)}{AUW^{1.39}}\ \underset{(.012)}{CLIMB^{.270}}\ \underset{(.049)}{WGWET^{.648}}$	.89	.27	27	14	-1	+16	-21	+2	10	EXP MAG:AUW EXP SIGN:WGWET IO:F-104,F-111
P40	$PROG_{100} = 2.79\ \underset{(.000)}{AUW^{1.06}}\ \underset{(.032)}{CLIMB^{.209}}\ \underset{(.011)}{WGTYPE^{.526}}$	.88	.27	28	15	+19	+4	-49	+20	23	EXP MAG:AUW IO:F-14
P41	$PROG_{100} = .00532\ \underset{(.000)}{AUW^{1.25}}\ \underset{(.014)}{ENERGY^{.655}}\ \underset{(.021)}{EWAUW^{.602}}$	.90	.25	30	14	-6	-6	-19	-6	9	RP:CUR:UNDER EXP MAG:AUW IO:F-105
P42	$PROG_{100} = .0373\ \underset{(.000)}{AUW^{1.16}}\ \underset{(.025)}{ENERGY^{.574}}\ \underset{(.022)}{AVAUW^{.258}}$	.90	.25	30	14	+5	-8	-35	+3	13	EXP MAG:AUW IO:F3D
P43	$PROG_{100} = .00421\ \underset{(.000)}{AUW^{1.18}}\ \underset{(.007)}{ENERGY^{.800}}\ \underset{(.021)}{WGWET^{.806}}$	.90	.25	30	14	-2	-10	-13	-7	8	EXP MAG:AUW EXP SIGN:WGWET RP:CUR:UNDER IO:F-101
P44	$PROG_{100} = .435\ \underset{(.000)}{AUW^{1.18}}\ \underset{(.005)}{PFFD^{.680}}\ \underset{(.024)}{EWAUW^{.560}}$	.89	.25	31	15	+1	+7	-30	-22	15	EXP MAG:AUW IO:F-105
P45	$PROG_{100} = 1.58\ \underset{(.000)}{AUW^{1.11}}\ \underset{(.019)}{PFFD^{.625}}\ \underset{(.017)}{AVAUW^{.266}}$	.91	.25	32	14	+10	+3	-48	-12	18	EXP MAG:AUW IO:F3D, F-14
P46	$PROG_{100} = 4.49\ \underset{(.000)}{AUW^{.944}}\ \underset{(.033)}{PFFD^{.537}}\ \underset{(.043)}{WGTYPE^{.419}}$	.88	.27	28	15	+20	-8	-53	+4	21	MCOL:r(PFFD) > .7 IO:F-14

Table 14 (continued)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg	Comments
P47	$PROG_{100} = 81.0\ \underset{(.002)}{AUW^{.711}}\ \underset{(.025)}{PFFD^{.514}}\ \underset{(.014)}{PRGDV^{-.701}}$	.90	.24	34	15	+2	+15	-26	-16	15	MCOL:r(PRGDV) > .8 EXP MAG:PRGDV IO:F4D
P48	$PROG_{100} = .113\ \underset{(.000)}{EW^{1.24}}\ \underset{(.007)}{SP^{.608}}\ \underset{(.011)}{AVAUW^{.240}}$	.94	.20	50	14	-6	-1	-27	+9	11	EXP MAG:EW IO:F3D
P49	$PROG_{100} = .0546\ \underset{(.000)}{EW^{1.25}}\ \underset{(.007)}{SP^{.741}}\ \underset{(.047)}{WGWET^{.577}}$	.92	.23	38	14	-11	-1	-9	+4	6	EXP SIGN:WGWET MCOL:r(SP) > .7 IO:F-104
P50	$PROG_{100} = .342\ \underset{(.000)}{EW^{1.11}}\ \underset{(.025)}{SP^{.510}}\ \underset{(.042)}{WGTYPE^{.355}}$	.91	.23	38	15	+7	-11	-32	+18	17	EXP MAG:EW IO:F-102
P51	$PROG_{100} = 4.06\ \underset{(.001)}{EW^{.943}}\ \underset{(.049)}{SP^{.452}}\ \underset{(.047)}{PRGDV^{-.545}}$	.91	.23	37	15	-7	+8	-14	+5	8	MCOL:r(PRGDV) > .8 EXP MAG:PRGDV IO:F-102
P52	$PROG_{100} = 4.15\ \underset{(.000)}{EW^{1.27}}\ \underset{(.001)}{SPPWR^{.365}}\ \underset{(.004)}{AVAUW^{.244}}$	.96	.17	71	14	-5	+11	-23	-4	11	EXP MAG:EW IO:F3D,F-100
P53	$PROG_{100} = 6.28\ \underset{(.000)}{EW^{1.15}}\ \underset{(.011)}{SPPWR^{.309}}\ \underset{(.050)}{WGTYPE^{.318}}$	.92	.22	44	15	+7	0	-28	+8	11	EXP MAG:EW
P54	$PROG_{100} = 37.6\ \underset{(.000)}{EW^{.978}}\ \underset{(.011)}{SPPWR^{.283}}\ \underset{(.014)}{WSDV^{.558}}$	.94	.20	54	15	-10	+13	-16	-8	12	MCOL:r(WSDV) > .7

Table 14 (continued)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) F-4	F-111	F-14	F-15	Abs Avg	Comments
P55	$PROG_{100} = 50.5\ \underset{(.000)}{EW^{.983}}\ \underset{(.017)}{SPPWR^{.290}}\ \underset{(.043)}{PRGDV^{-.502}}$	.92	.21	45	15	-6	+16	-12	-5	10	MCOL:r(PRGDV) > .8 EXP MAG:PRGDV IO:F-102
P56	$PROG_{100} = .105\ \underset{(.000)}{EW^{1.42}}\ \underset{(.003)}{CLIMB^{.247}}\ \underset{(.004)}{AVAUW^{.264}}$	.95	.18	60	14	-4	+20	-31	+4	15	EXP MAG:EW IO:F3D,F-100,F-111
P57	$PROG_{100} = .428\ \underset{(.000)}{EW^{1.23}}\ \underset{(.028)}{CLIMB^{.192}}\ \underset{(.020)}{WGTYPE^{.414}}$	.91	.23	37	15	+11	+6	-37	+17	18	EXP MAG:EW
P58	$PROG_{100} = 4.31\ \underset{(.000)}{EW^{1.04}}\ \underset{(.038)}{CLIMB^{.167}}\ \underset{(.008)}{WSDV^{.658}}$	.92	.22	44	15	-10	+19	-19	-1	12	EXP MAG:EW MCOL:r(WSDV) > .7 IO:F-111
P59	$PROG_{100} = .00578\ \underset{(.000)}{EW^{1.27}}\ \underset{(.007)}{ENERGY^{.591}}\ \underset{(.018)}{AVAUW^{.214}}$	.94	.20	50	14	-2	-6	-27	+1	9	EXP MAG:EW IO:F3D
P60	$PROG_{100} = .00112\ \underset{(.000)}{EW^{1.27}}\ \underset{(.003)}{ENERGY^{.769}}\ \underset{(.034)}{WGWET^{.588}}$	.93	.21	44	14	-8	-7	-10	-8	8	EXP MAG:EW EXP SIGN:WGWET RP:CUR:UNDER IO:F-104
P61	$PROG_{100} = .309\ \underset{(.000)}{EW^{1.22}}\ \underset{(.009)}{PFFD^{.606}}\ \underset{(.016)}{AVAUW^{.224}}$	.94	.20	48	14	+4	+5	-38	-13	15	EXP MAG:EW IO:F3D,F-14
P62	$PROG_{100} = 4.78\ \underset{(.000)}{EW^{.955}}\ \underset{(.027)}{PFFD^{.456}}\ \underset{(.024)}{WSDV^{.550}}$	.93	.21	46	15	-3	+8	-26	-15	13	MCOL:r(WSDV) > .7

Table 14 (continued)

Eq. No.	Equation	R^2	SEE	F	N	F-4	F-111	F-14	F-15	Abs Avg	Comments
		Statistics				Relative Deviations (%)					
P63	$PROG_{100} = 8.68\ \underset{(.000)}{EW^{.907}}\ \underset{(.016)}{PFFD^{.501}}\ \underset{(.027)}{PRGDV^{-.548}}$	.93	.21	45	15	0	+12	-23	-15	12	EXP MAG:PRGDV MCOL:r(PRGDV) > .7
	SIZE/CONSTRUCTION, PROGRAM										
P64	$PROG_{100} = 285\ \underset{(.004)}{AUW^{.810}}\ \underset{(.005)}{WSDV^{.944}}$	.83	.30	30	15	-2	+10	-13	+9	8	IO:F4D,F-86,F-89
P65	$PROG_{100} = 22.3\ \underset{(.000)}{EW^{1.03}}\ \underset{(.002)}{WSDV^{.834}}$	.90	.24	51	15	-7	+5	-13	+9	8	EXP MAG:EW IO:F-104
	SIZE/PERFORMANCE/TECHNOLOGY INDEX										
	Ncne										

XII. SELECTION OF RECOMMENDED EQUATION SET

The representative equation sets for the four size/performance variable combinations (airframe unit weight/speed, airframe unit weight/specific power, airframe unit weight/climb rate, and airframe unit weight/composite performance index) as well as the equation set containing the "best" estimating relationship for each cost element (irrespective of the size/performance variable combination) are listed in Tables 15 through 19. Additionally, the post-1960 equation set is listed in Table 20. A comparison of these equation sets based on the relative deviations of the four most recent fighters (F-4, F-111, F-14, and F-15) is provided in Table 21. Based on a review of these tables, the following observations are made:

(1) No acceptable estimating relationships incorporating size/performance variables could be determined for the labor, material, and development support cost elements.

(2) Based on the standard error of estimate, little difference exists between the equation sets derived by statistical methods. Moreover, only one CER reaches our standard error of estimate goal of 0.18 (see Table 22).

(3) Based on relative deviations with respect to the F-4, F-111, F-14, and F-15 (Table 21), the two sets that do the best are airframe unit weight/speed and post-1960. The post-1960 result is not too surprising, however, since the weight-scaling relationships are based on the same four aircraft.

(4) Based on comparisons of: (a) the standard errors of individual estimating relationships; and (b) relative deviations with respect to the F-4, F-111, F-14, and F-15, there is no advantage in mixing the set size/performance variables.

(5) With the exception of the number of test aircraft (for the flight test cost element), the only construction/program variable that was influential in improving the quality of the CERs was the weapon system designator (WSDV).

Table 15

REPRESENTATIVE SET: AIRFRAME UNIT WEIGHT AND SPEED

Estimating Relationship	Statistics				Residual Pattern
	R^2	SEE	F	N	
$ENGR_{100} = .0000308\ AUW^{1.07} SP^{1.30}$ (.000) (.000)	.93	.24	85	15	None
$TOOL_{100} = .0981\ AUW^{.627} SP^{.740}$ (.026) (.027)	.64	.39	11	15	None
$LABR_{100} = 6.55\ AUW^{.774} WSDV^{.558}$ (a) (.005) (.049)	.75	.31	18	15	None
$MATL_{100} = 5.68\ AUW^{.999} WSDV^{.935}$ (a) (.003) (.011)	.82	.36	27	15	CUR: UNDER
$DS = 1.08 * ENGRC_1$ (b)	—	—	—	15	—
$FT = .0000215\ AUW^{.771} SP^{1.62} TESTAC^{1.30}$ (.061) (.007) (.003)	.80	.59	15	15	None
$QC_{100} = .125 * LABR_{100}$	—	—	—	8	—
$PROG_{100} = .450\ AUW^{.951} SP^{.800}$ (.001) (.007)	.82	.31	28	15	None

[a] Since no acceptable estimating relationships incorporating airframe unit weight and speed could be determined, these alternative estimating relationships were inserted to complete the equation set.

[b] $ENGRC_1 = \$27.50 * ENGR_{100} * 100^{-.164}$.

Table 16

REPRESENTATIVE SET: AIRFRAME UNIT WEIGHT AND SPECIFIC POWER

Estimating Relationship		Statistics				Residual Pattern
		R^2	SEE	F	N	
$ENGR_{100} = .0290\ AUW^{1.24} SPPWR^{.713}$ (.000) (.000)		.96	.19	140	15	CUR: UNDER
$TOOL_{100} = 5.93\ AUW^{.700} SPPWR^{.444}$ (.007) (.010)		.69	.36	13	15	None
$LABR_{100} = 6.55\ AUW^{.774} WSDV^{.558}$ (.005) (.049)	(a)	.75	.31	18	15	None
$MATL_{100} = 5.68\ AUW^{.999} WSDV^{.935}$ (.003) (.011)	(a)	.82	.36	27	15	CUR: UNDER
$DS = 1.08 * ENGRC_1$	(b)	—	—	—	15	—
$FT = .179\ AUW^{.940} SPPWR^{.951} TESTAC^{1.25}$ (.013) (.002) (.002)		.85	.52	20	15	None
$QC_{100} = .125 * LABR_{100}$		—	—	—	8	—
$PROG_{100} = 290\ AUW^{.805} SPPWR^{.349} WSDV^{.557}$ (.001) (.012) (.041)		.90	.25	32	15	None

[a] Since no acceptable estimating relationships incorporating airframe unit weight and specific power could be determined, these alternative estimating relationships were inserted to complete the equation.

[b] $ENGRC_1 = \$27.50 * ENGR_{100} * 100^{-.164}$

Table 17

REPRESENTATIVE SET: AIRFRAME UNIT WEIGHT AND CLIMB RATE

Estimating Relationship	Statistics				Residual Pattern
	R^2	SEE	F	N	
$ENGR_{100} = .0000396\ \underset{(.000)}{AUW^{1.46}}\ \underset{(.000)}{CLIMB^{.483}}$	.90	.29	55	15	CUR: UNDER
$TOOL_{100} = .110\ \underset{(.003)}{AUW^{.846}}\ \underset{(.038)}{CLIMB^{.278}}$	.62	.40	10	15	None
$LABR_{100} = 6.55\ \underset{(.005)}{AUW^{.774}}\ \underset{(.049)}{WSDV^{.558}}$ (a)	.75	.31	18	15	None
$MATL_{100} = 5.68\ \underset{(.003)}{AUW^{.999}}\ \underset{(.011)}{WSDV^{.935}}$ (a)	.82	.36	27	15	CUR: UNDER
$DS = 1.08 * ENGRC_1$ (b)	--	--	--	15	--
$FT = .0000177\ \underset{(.004)}{AUW^{1.27}}\ \underset{(.011)}{CLIMB^{.601}}\ \underset{(.002)}{TESTAC^{1.44}}$	.79	.61	14	15	None
$QC_{100} = .125 * LABR_{100}$	--	--	--	8	--
$PROG_{100} = 285\ \underset{(.004)}{AUW^{.810}}\ \underset{(.005)}{WSDV^{.944}}$ (a)	.83	.30	30	15	None

[a] Since no acceptable estimating relationships incorporating airframe unit weight and climb rate could be determined, these alternative estimating relationships were inserted to complete the equation set.

[b] $ENGRC_1 = \$27.50 * ENGR_{100} * 100^{-.164}$.

Table 18

REPRESENTATIVE SET: AIRFRAME UNIT WEIGHT AND COMPOSITE PERFORMANCE INDEX

Estimating Relationship	Statistics				Residual Pattern
	R^2	SEE	F	N	
$ENGR_{100} = .000198\ AUW^{1.08} PFFD^{1.28}$ (.000) (.000)	.96	.18	146	15	None
$TOOL_{100} = .295\ AUW^{.657} PFFD^{.684}$ (.020) (.027)	.64	.39	11	15	None
$LABR_{100} = 6.55\ AUW^{.774} WSDV^{.558}$ (a) (.005) (.049)	.75	.31	18	15	None
$MATL_{100} = 5.68\ AUW^{.999} WSDV^{.935}$ (a) (.003) (.001)	.82	.36	27	15	CUR: UNDER
$DS = 1.08 * ENGRC_1$ (b)	--	--	--	15	--
$FT = .000313\ AUW^{.807} PFFD^{1.54} TESTAC^{1.21}$ (.051) (.007) (.006)	.80	.59	15	15	None
$QC_{100} = .125 * LABR_{100}$	--	--	--	8	--
$PROG_{100} = 1.39\ AUW^{.951} PFFD^{.810}$ (.000) (.030)	.85	.29	33	15	None

[a] Since no acceptable estimating relationships incorporating airframe unit weight and the composite performance index could be determined, these alternative estimating relationships were inserted to complete the equation set.

[b] $ENGRC_1 = \$27.50 * ENGR_{100} * 100^{-.164}$.

Table 19

REPRESENTATIVE SET: SINGLE BEST EQUATION FOR EACH COST ELEMENT

Estimating Relationship	Statistics				Residual Pattern
	R^2	SEE	F	N	
$ENGR_{100} = .000198\ \underset{(.000)}{AUW^{1.08}}\ \underset{(.000)}{PFFD^{1.28}}$	.96	.18	146	15	None
$TOOL_{100} = .876\ \underset{(.003)}{EW^{.865}}\ \underset{(.017)}{SPPWR^{.382}}$	.73	.33	17	15	None
$LABR_{100} = 6.55\ \underset{(.005)}{AUW^{.774}}\ \underset{(.049)}{WSDV^{.558}}$ (a)	.75	.31	18	15	None
$MATL_{100} = 5.68\ \underset{(.003)}{AUW^{.999}}\ \underset{(.011)}{WSDV^{.935}}$ (a)	.82	.36	27	15	CUR: UNDER
$DS = 1.08 * ENGRC_1$ (b)	--	--	--	15	--
$FT = .00623\ \underset{(.002)}{EW^{1.24}}\ \underset{(.002)}{SPPWR^{.846}}\ \underset{(.001)}{TESTAC^{1.25}}$	.88	.45	28	15	None
$QC_{100} = .125 * LABR_{100}$	--	--	--	8	--
$PROG_{100} = 290\ \underset{(.001)}{AUW^{.805}}\ \underset{(.012)}{SPPWR^{.349}}\ \underset{(.041)}{WSDV^{.557}}$	.90	.25	32	15	None

[a] Since no acceptable estimating relationships incorporating airframe unit weight and a performance variable could be determined, these alternative estimating relationships were inserted to complete the equation set.

[b] $ENGRC_1 = \$27.50 * ENGR_{100} * 100^{-.164}$.

Table 20

REPRESENTATIVE SET: POST-1960 SAMPLE
(F-4, F-111, F-14, and F-15)(a)

$$ENGR_{100} = 2.31\ AUW^{.887}$$

$$TOOL_{100} = 1.38\ AUW^{.883}$$

$$LABR_{100} = 23.0 * AUW^{.678}$$

$$MATL_{100} = 127\ AUW^{.766}$$

$$DS = .68 * ENGRC_{1}\ (b)$$

$$FT = 27100\ TESTAC^{.687}$$

$$QC_{100} = .134 * LABR_{100}$$

$$PROG_{100} = 550\ AUW^{.812}$$

(a)Determined by visual rather than statistical means.

(b)$ENGRC_{100} = \$27.50 * ENGR_{100} * 100^{-.164}$.

Table 21

RELATIVE DIFFERENCES BETWEEN ACTUALS AND REPRESENTATIVE EQUATION SET ESTIMATES (a)
(In percentages)

	Equation Set					
Aircraft	AUW/SPEED (Table 15)	AUW/SPPWR (Table 16)	AUW/CLIMB (Table 17)	AUW/PFFD (Table 18)	Single Best CER (Table 19)	Post-1960 Sample (Table 20)
Sum of Individual CERs[b]						
F-4	+ 4	+ 6	+ 8	+13	+10	- 0
F-111	+ 2	+12	+20	+ 9	+ 9	+11
F-14	-19	-16	-23	-30	-25	-11
F-15	+ 0	-14	- 3	-26	-19	+ 4
Average (absolute)	6	12	14	20	16	6
Total Program CER						
F-4	+ 2	- 6	- 2	+12	- 6	- 4
F-111	+ 3	+16	+10	+ 8	+16	+ 7
F-14	-22	-19	-13	-40	-19	-16
F-15	+ 7	-12	+ 9	-25	-12	+ 7
Average (absolute)	8	13	8	21	13	8

[a] (Actual-Estimate)/Actual.

[b] A breakdown by cost element may be found in Appendix B. Labor rates applied to those cost elements estimated in hours are as follows:

Engineering	\$27.50/hr.
Tooling	\$25.50/hr.
Manufacturing labor	\$23.50/hr.
Quality control	\$24.00/hr.

Table 22

SUMMARY OF STANDARD ERRORS OF ESTIMATE

Cost Element	Percentage of Total Cost at Q = 100	Equation Set AUW/SP	AUW/SPPWR	AUW/CLIMB	AUW/PFFD	Single Best
Engineering	20	.24	.19	.29	.18	.18
Tooling	15	.39	.36	.40	.39	.33
Labor	32	.31	.31	.31	.31	.31
Material	13	.36	.36	.36	.36	.36
Dev support	8	--	--	--	--	--
Flight test	8	.59	.52	.61	.59	.45
Quality control	4	--	--	--	--	--
Total Program	100	.31	.25	.30	.29	.25

(6) Based on a comparison of relative deviations (Table 21), little difference exists between the sum of elements approach and the total program CER approach.

Since there is little, if any, advantage to mixing the set size/performance variables, the recommended equation set will be chosen from among the four sets that maintain the integrity of the size/performance variable combination plus the post-1960 set. Of the four sets derived by regression analysis, the one utilizing airframe unit weight and specific power probably has the best statistical properties while the set utilizing airframe unit weight and speed does the best job with respect to the four most recent fighters. Thus, of the statistically derived sets, airframe unit weight/speed and airframe unit weight/specific power are preferred. However, on balance, we recommend the post-1960 set for the following reasons:

1. The set is based on aircraft that are still in operation and, in some cases, still in production. Thus, the set is based on aircraft that are fairly familiar, which should in turn make any necessary equation adjustments easier.

2. The magnitude of the size variable exponents is more credible than in the statistically derived sets.

XIII. INCORPORATION OF F-16 AND F-18

Subsequent to the completion of the present detailed analysis, but prior to the formal publication of this Note, cost data on the F-16 and F-18 airframes became available. Consequently, a brief examination was undertaken to determine whether inclusion of the F-16 and F-18 in the database would dictate modification of the recommended set of CERs (Table 20). This examination consisted of the following two steps:

(1) assessing how well the existing equation set estimates F-16 and F-18 costs; and,

(2) examining cost scattergrams that include the F-16 and F-18 to see whether any changes in the visually fit equations are suggested.

ADJUSTMENT OF F-16 PRODUCTION DATA

Normally, in order to arrive at the cumulative total production cost for the first 100 F-16 airframes, we would take recorded data for the two prototypes, eight FSD aircraft, and the first 90 aircraft in the USAF FY77/78 buy of 105 aircraft. However, because of the concurrent multinational coproduction effort (General Dynamics produces all of the forward fuselages and approximately half of the quantity of all other components), the recurring factory labor and materials cost obtained in that way would be understated because of the additional learning benefit associated with the higher overall production. Therefore, the production labor and material costs for the F-16 are based on 90 "equivalent" aircraft. The estimate for the 90 equivalent aircraft was obtained by taking the costs for the first 90 production units of *each component* plus the integration and assembly effort for the first 90 aircraft and then taking their sum.

USING THE EXISTING EQUATION SET TO ESTIMATE F-16 AND F-18 COSTS

A comparison of F-16 and F-18 actual costs to estimated costs using the CERs provided in Table 20 is presented in Table 23.[1] Based on this table, the following observations are made:

- In total, the fighter subsample equation set overstates F-16 costs by about 25 percent and understates F-18 costs by about 20 percent.
- The relative deviations across cost elements for the F-18 show a degree of uniformity while those for the F-16 show considerable divergence--from roughly +10 to less than -60 percent.
- Of most importance is the fact that, for the F-16, the single most important[2] cost category--manufacturing labor--is overestimated by about 50 percent.

The fact that the F-16 is overestimated and the F-18 underestimated is not all that surprising: The F-16 program placed a great deal of emphasis on maintaining cost goals while the F-18 program faced a particularly involved two-contractor development. Specific reasons cited for the F-16's relatively low cost and the F-18's relatively high cost are listed below.

F-16

(1) Emphasis on Simplicity[3]

a. Structural materials are high percentage aluminum (79%) and very low percentage steel, titanium, and composites (11%).

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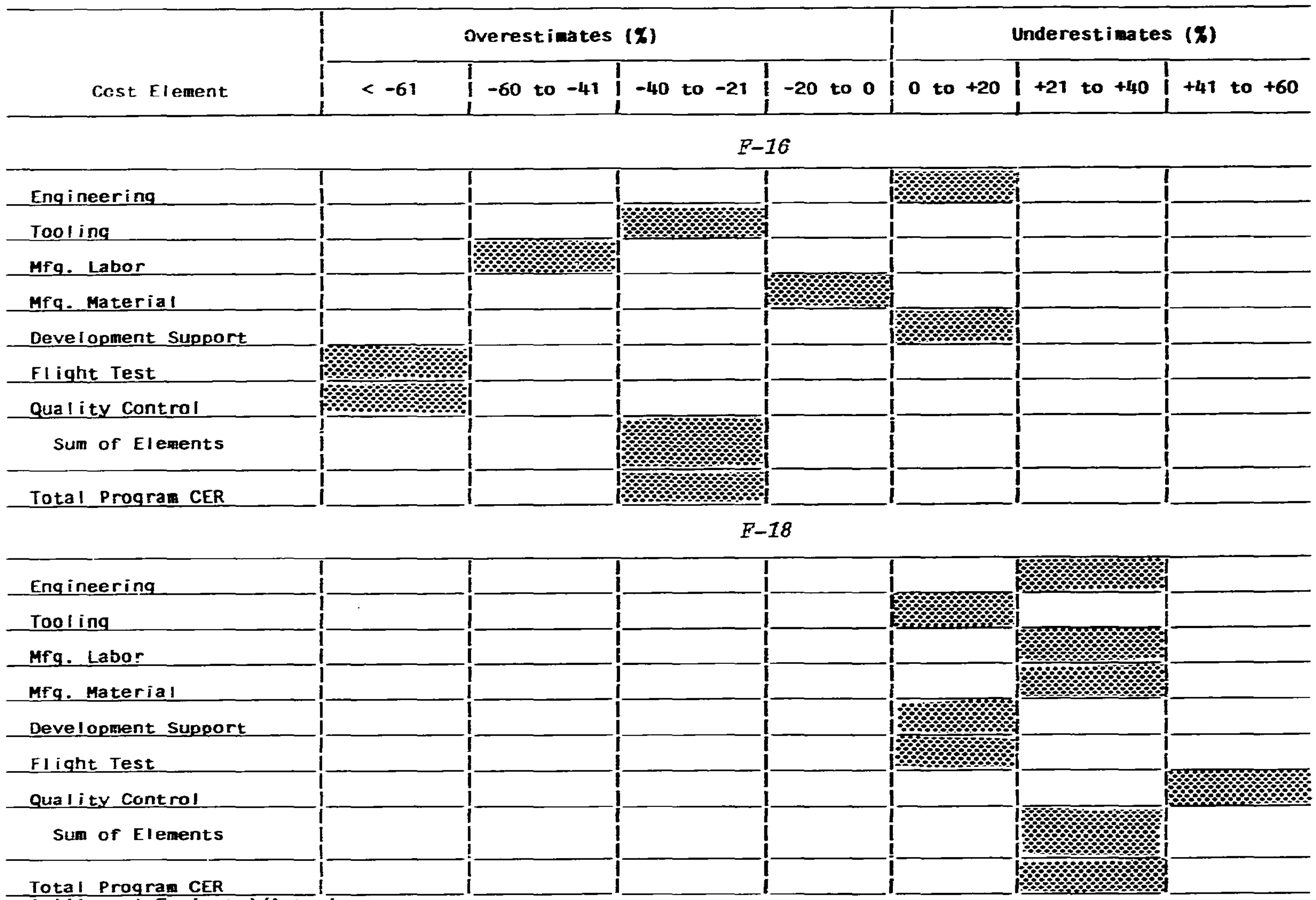
[1]More precise values could not be provided because of proprietary restrictions.

[2]In terms of proportion of total cost.

[3]List of examples provided by Gordon Fuqua of General Dynamics Fort Worth Division.

Table 23

COMPARISON OF F-16 AND F-18 ESTIMATED COSTS WITH ACTUALS: RELATIVE DEVIATIONS (a)



(a)(Actual-Estimate)/Actual

b. Extensive use of standard manufacturing methods--60 percent of parts are sheet aluminum.
c. Used a fully developed engine common to the F-15.
d. Relatively few fastener types employed (50 for F-16 versus 250 for F-111).
e. Extensive use of off-the-shelf equipment items (257 out 373 F-16 items were off-the-shelf; almost all of items on B-58 and F-111 were new).

(2) Adherence to "Design-to-Cost" Philosophy: No major design changes were introduced by the Air Force or General Dynamics during FSD and early production; in fact, the first group of major changes to the F-16 did not occur until the 612th aircraft.[4]

(3) Relatively high production rate achieved early in program (within 2 years of the first delivery, General Dynamics had delivered roughly another 175 aircraft and the Europeans another 50).[5]

F-18

(1) Extensive use of composites: Roughly 11 percent of the F-18 structure weight is composites, far higher than any prior aircraft.[6]

(2) Carrier-based F-18 is actually an adaptation of land-based YF-17, an adaptation that was complicated by the fact that the original design was done by Northrop while the redesign was primarily the responsibility of McDonnell.[7,8]

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[4]This initial set of modifications is known as Phase 1 of the Multinational Staged Improvement Program or Engineering Change Proposal 350 (Gordon Fuqua, GD Fort Worth).

[5]See Ref. 6, p. 100.

[6]Note, however, that the AV-8B, which was also developed by McDonnell Douglas and in roughly the same timeframe as the F-18, has approximately 25 percent of its structure weight in composites.

[7]"On January 22, 1976, the U.S. Navy gave McDonnell Douglas the go-ahead to develop the carrier-based F-18. Northrop, the company that conceived the basic design of the F-18 as the F-17, became an associate contractor, assigned 40 percent of airframe development and airframe production" (see Ref. 7, p. 164).

[8]It has also been suggested that F-18 costs could be expected to be higher than the norm because the aircraft was designed to satisfy both fighter and attack missions. However, in retrospect we do not feel that this was a major contributor to the F-18's relatively high cost because the fighter and attack configurations turned out to be so similar (in the attack version, a FLIR and laser tracker replace fuselage-mounted Sparrow missiles).

(3) Difficulty in Northrop/McDonnell relationship (at one point, the two firms were engaged in a court battle).

(4) Relatively slow production rate buildup: FSD (11 aircraft) was followed by pilot production (9 aircraft) and limited production (25 aircraft) prior to initial full-scale production (60 aircraft).

EXAMINING UPDATED SCATTERGRAMS

As indicated previously, six of the eight CERs in the recommended fighter equation set were determined by visually fitting a line to 4 observations (F-4, F-111, F-14, and F-15). The results of a reexamination of the cost-weight plots, updated to include the F-16 and F-18, are presented in Table 24. In the course of this reexamination, which was an admittedly subjective process, less emphasis was given to the F-16 than to the other five aircraft in the sample. It was given less emphasis because we did not feel that it was likely to be representative of future military aircraft development and production.

Overall, the changes made as a result of updating the database are relatively minor--labor hours increase by about 10 percent while material costs are now subject to a 92 percent weight-scaling factor rather than an 85 percent factor.

Table 24

RESULTS OF UPDATING THE COST-WEIGHT PLOTS

Part A: Recommended Equation without F-16 and F-18	Revision Suggested by Addition of F-16 and F-18? (Yes/No)	Part B: Recommended Equation with F-16 and F-18
$ENGR_{100}$ $2.31\ AUW^{.887}$	No	$ENGR_{100} = 2.31\ AUW^{.887}$
$TOOL_{100} = 1.38\ AUW^{.883}$	No	$TOOL_{100} = 1.38\ AUW^{.883}$
$LABR_{100} = 23.0\ AUW^{.678}$	Yes	$LABR_{100} = 25.4\ AUW^{.678}$
$MATL_{100} = 127\ AUW^{.766}$	Yes	$MATL_{100} = 43.3\ AUW^{.878}$
$DS = .68 * ENGRC_1$ (a)	Yes	$DS = .75 * ENGRC_1$
$FT = 27100\ TESTAC^{.687}$	No	$FT = 27100\ TESTAC^{.687}$
$QC_{100} = .134 * LABR_{100}$	Yes	$QC_{100} = .142 * LABR_{100}$
$PROG_{100} = 550\ AUW^{.812}$	No	$PROG_{100} = 550\ AUW^{.812}$

(a) $ENGRC_1 = \$27.50 * ENGR_{100} * 100^{-.164}$

XIV. CONCLUDING REMARKS

RECOMMENDED EQUATION SET

The equation set that we believe is the most representative and applicable to the widest range of estimating situations is displayed in Table 25. With the exception of development support and quality control, each of the estimating relationships shown in Table 25 has been visually fitted to the data and is based on a sample consisting of only the six most recent fighters--those with first flight dates subsequent to 1960. This is a result of observations made during the course of the study that raised questions concerning the applicability of some of the older fighters in the sample to fighters of the future. Consequently, additional analysis limited to post-1960 fighters was undertaken. As a result of this additional analysis, we concluded that the more limited post-1960 experience would be a better guide to the future. The post-1960 fighters that served as the basis for the equations in Table 25 have characteristic values that span the ranges shown below.

Characteristic	Post-1960 Database Range
Airframe unit weight (lb)	9,565 - 33,150
Empty weight (lb)	14,062 - 46,170
Speed (knots)	1,000+ - 1,250+
Specific power (hp/lb)	1.94 - 4+
Climb rate (ft/min)	11,600 - 50,000+
Number of flight test aircraft	7 - 20

CONSTRUCTION/PROGRAM VARIABLES

With the exception of a variable that distinguishes the older fighters (which were essentially gun platforms) from the more modern fighters with sophisticated fire control and missile armament, our attempts to incorporate construction and program characteristics were not successful. Although variables characterizing the equipment placed within the airframe structure were frequently found to be statistically

Table 25

RECOMMENDED SET OF FIGHTER AIRFRAME CERS (a)

(Based on post-1960 fighters)

$$ENGR_{100} = 2.31\ AUW^{.887}$$

$$TOOL_{100} = 1.38\ AUW^{.883}$$

$$LABR_{100} = 25.4\ AUW^{.678}$$

$$MATL_{100} = 43.3\ AUW^{.878}$$

$$DS = .75 * ENGRC_{1}\ \text{(b)}$$

$$FT = 27100\ TESTAC^{.687}$$

$$QC = .142 * LABR_{100}$$

$$PROG_{100} = 550\ AUW^{.812}$$

(a)Repeated from Part B of Table 24.

(b)$ENGRC_1 = \$27.50 * ENGR_{100} * 100^{-.164}$

significant, they did not, as a rule, result in any substantial improvement in the quality of the equations. In most cases, the equations incorporating such variables did not produce results that we viewed as credible. Moreover, even in those few instances where the equations did produce credible results, the reduction in the standard error of estimate was never more than two or three percentage points.

TECHNOLOGY INDEX

We were able to identify only one instance (for the engineering cost element) in which the objective technology index (PFFD) was significant at the 5 percent level in the context of the tested variable combination (size/performance/technology index):

$$\frac{ENGR}{100} = .00242\ AUW^{1.13}_{(.000)}\ SPPWR^{.367}_{(.021)}\ PFFD^{.697}_{(.016)}$$

R^2	SEE	F	N
.97	.16	134	15

where

AUW = airframe unit weight (lb)
PFFD = predicted first flight date (months since January 1, 1940)
SPPWR = specific power (hp/lb)

However, the correlation of AUW and SPPWR with the technology index is greater than 0.9. Furthermore, the equation offers little advantage (in terms of the standard error of estimate) over alternative forms without the technology index. We conclude that the objective technology index, as now defined, is of little benefit to fighter airframe CERs. The reason it did so poorly in our analysis is that it is really a composite performance variable and consequently very highly correlated with most of the performance variables we tested here. It should be noted that when the measure is treated as a performance variable rather than as a technology index, it does about as well as speed and specific power as an explanatory variable.

COMPARISON TO FULL ESTIMATING SAMPLE EQUATION SET

A comparison of how accurately the full estimating equation set (Table 26) and the fighter subsample equation set (Table 25) estimate the costs of the six post-1960 fighters is provided in Table 27. On an *overall* average basis, the fighter equation set does slightly better. However, there is a considerable difference between the two sets with respect to which will produce the higher estimate. As shown below, the fighter equation set produces considerably higher estimates for the F-16 and F-18 than does the full estimating sample equation set:

	Percentage by Which Fighter Set Estimate Exceeds All-Mission Set Estimate	
Aircraft	Sum of Elements	Total Program CER
F-16	8	3
F-18	22	22

However, for the remaining fighters, all of which are heavier and faster than the F-16 and F-18, the all-mission type equation set tends to produce estimates that are greater than those produced by the fighter sample equation set:

	Percentage by Which All-Mission Set Estimate Exceeds Fighter Set Estimate	
Aircraft	Sum of Elements	Total Program CER
F-4	8	11
F-111	4	1
F-14	4	4
F-15	15	13

Table 26

RECOMMENDED SET OF AIRFRAME CERs BASED ON FULL ESTIMATING SAMPLE

Equation	R^2	SEE	F	N
$ENGR_{100} = .0103\ EW^{.777}\ SP^{.894}$ (.000) (.000)(a)	.72	.55	13	13
$TOOL_{100} = .0201\ EW^{.777}\ SP^{.696}$ (.000) (.000)	.92	.25	56	13
$LABR_{100} = .141\ EW^{.820}\ SP^{.484}$ (.000) (.013)	.88	.31	38	13
$MATL_{100} = .241\ EW^{.921}\ SP^{.621}$ (.000) (.003)	.91	.30	51	13
$DS = .0251\ EW^{.630}\ SP^{1.30}$ (.016) (.012)	.54	.82	6	13
$FT = .687\ EW^{.325}\ SP^{.822}\ TESTAC^{1.21}$ (.032) (.037) (.010)	.83	.48	15	13
$QC_{100} = .076 \times LABR_{100}$ if cargo aircraft	--	--	--	2
$= .133 \times LABR_{100}$ if non-cargo aircraft	--	--	--	11
$PROG_{100} = 2.57\ EW^{.798}\ SP^{.736}$ (.000) (.003)	.85	.36	29	13

SOURCE: N-2283/1-AF, Table 1.

NOTES: Statistics in right-hand columns are coefficient of determination, standard error of estimate (logarithm), F-statistic, and sample size. Numbers in parentheses are significance levels of individual variables.

- DS = development support cost (thousands of 1977 dollars).
- $ENGR_{100}$ = cumulative engineering hours for 100 aircraft (thousands).
- EW = empty weight (lb).
- FT = flight test cost (thousands of 1977 dollars).
- $LABR_{100}$ = cumulative manufacturing labor hours for 100 aircraft (thousands).
- $MATL_{100}$ = cumulative manufacturing material dollars for 100 aircraft (thousands of 1977 dollars).
- QC_{100} = cumulative quality control hours for 100 aircraft (thousands).
- $PROG_{100}$ = cumulative total program cost for 100 aircraft (thousands of 1977 dollars).
- SP = maximum speed (kn).
- $TESTAC$ = number of flight test aircraft.
- $TOOL_{100}$ = cumulative tooling hours for 100 aircraft (thousands).

Table 27

RELATIVE ACCURACY OF ESTIMATES OBTAINED USING
FULL ESTIMATING SAMPLE AND FIGHTER SUBSAMPLE EQUATION SETS

Aircraft	Percentage by Which Actual Cost Exceeds (+) or Falls Short (-) of Estimated Cost			
	Sum of Elements		Total Program CER	
	All Mission Sample	Fighter Sample	All Mission Sample	Fighter Sample
F-4	-14	- 5	-16	- 4
F-111	+ 3	+ 6	+ 7	+ 7
F-14	-22	-17	-20	-16
F-15	-15	- 1	- 5	+ 7
F-16	-23	-33	-20	-23
F-18	+33	+18	+36	+22
Average of Absolute Values	18	13	17	13
Number Underestimated (+)	2	2	2	3
Number Overestimated (-)	4	4	4	3

Exactly which equation set will provide the higher estimate in any given situation depends on a number of factors including not only the aircraft's airframe unit weight and speed, but also the relative difference in its empty weight and airframe unit weight. In general, however, it would appear that the all-mission type equation set will produce higher estimates for heavier, faster fighters while the fighter equation set will produce higher estimates for smaller, "slower" fighters.

COST-QUANTITY SLOPES

Minimum, maximum, and average cost-quantity slopes for the fighter aircraft subsample are provided in Table 28. However, the recommended equation set (Table 25) is based on a sample limited to post-1960 aircraft. Consequently, average cumulative total slopes of the post-1960 sample are determined and compared to the full fighter sample (equivalent exponents in parentheses):

Table 28

CUMULATIVE TOTAL COST-QUANTITY SLOPES

	Engineering	Tooling	Mfg. Labor	Mfg Material	Quality Control	Total Program
Number of observations	17	17	17	17	10	17
Range (%)	110-124	110-158	142-182	140-200	146-234	124-144
Average (%)	116	124	156	172	170	132
Exponent	.214	.310	.642	.782	.760	.400

NOTES: Based on first 200 units; cumulative average slope = cumulative total slope divided by two.

Cost Element	Full Fighter Sample %	Post-1960 Fighter Sample %
Engineering	116	112 (.163)
Tooling	124	120 (.263)
Manufacturing labor	156	158 (.660)
Manufacturing material	172	166 (.731)
Quality control	170	164 (.714)
Total program cost	132	128 (.356)

As indicated, the differences are slight and hardly a basis for drawing any conclusions. Nevertheless, the slopes based on the post-1960 sample are recommended for consistency with the recommended equation set.

FULLY BURDENED LABOR RATES

All cost elements estimated directly in dollars are in 1977 dollars. Suggested 1977 fully burdened hourly labor rates (and those used to estimate total program cost) are:

Engineering	27.50
Tooling	25.50
Manufacturing labor	23.50
Quality control	24.00

For estimates in 1986 dollars, the following hourly labor rates and adjustment factors are suggested:

Engineering	59.10
Tooling	60.70
Manufacturing labor	50.10
Quality control	55.40
Manufacturing material (index)	1.94
Development support (index)	1.94
Flight test (index)	1.94
Total program (index)	2.13

The 1986 labor rates are based on data provided by seven contractors:

	Hourly Rates ($)		
Labor Category	Average	Range	Range about Average (%)
Engineering	59.10	47.70 - 70.00	-19, +18
Tooling	60.70	56.50 - 65.00	- 7, + 7
Manufacturing labor	50.10	41.70 - 58.00	-17, +16
Quality Control	55.40	49.10 - 62.60	-11, +13

Note that with the exception of tooling, the range about the average rate is at least + or -10%. Such differences could arise from differences in accounting practices, business bases, and capital investment. Irrespective of cause, however, labor rate variation is one more component of a larger uncertainty which already includes the error associated with statistically derived estimating relationships and questions about the proper cost-quantity slope. Furthermore, in addition to the intercontractor differences, these rates are also subject to temporal change--accounting procedures, relative capital/labor ratio, etc. Thus, the 1986 fully burdened rate is qualitatively different than the 1977 rate. Unfortunately, trying to estimate the magnitude of such quality changes, even very crudely, is beyond the scope of this analysis.

The material, development support, and flight test escalation indexes are based on data provided in AFR 173-13.[1] For the years 1977-1984, the airframe index presented in Table 5-3 ("Historical Aircraft Component Inflation Indices") was used. For the years 1985 and 1986, the aircraft and missile procurement index presented in Table 5-2 ("USAF Weighted Inflation Indices Based on OSD Raw Inflation and Outlay Rates") was used. The total program cost adjustment factor was then determined on the basis of a weighted average (at q = 100) of the individual cost elements.

FINAL COMMENTS

The recommended equation set uses only one variable--airframe unit weight--and is based on a subsample consisting of six post-1960 fighters. This equation set, which was visually fit to the data, provides results that we believe to be more credible than those produced by multiple least-squares regression analysis of the full fighter aircraft sample.

The ultimate test of the set's usefulness will be its ability to estimate the cost of future fighters. Unfortunately (from an estimating point of view), airframes are changing dramatically with respect to materials (e.g., more extensive use of composites), design concepts (e.g., concepts to increase fuel efficiency and to reduce radar cross-section), and manufacturing techniques (e.g., utilization of computers and robots). We believe the material and design changes will act to increase unit costs but are uncertain of the net impact of capital equipment changes. In any case, it is unlikely that any of the equation sets presented in this document will overestimate the costs of future fighters.

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[1]See Ref. 8.

Appendix A

CORRELATION MATRIXES

This appendix contains correlation matrixes for the "basic" fighter estimating sample (15 aircraft).[1] Table A.1 provides Pearson correlation coefficients for all possible pairwise combinations of dependent and independent variables. Table A.2 provides coefficients for all possible pairwise combinations of independent variables.

[1]These correlation coefficients were used in conjunction with the work completed prior to the incorporation of the F-16 and F-18.

Table A.1

CORRELATION MATRIX: COST VARIABLES WITH POTENTIAL EXPLANATORY VARIABLES

EXPLANATORY VARIABLES	COST VARIABLES						
	ln ENGR	ln TOOL	ln LABR	ln MATL	ln DEVSPT	ln FLTTST	ln PROG
SIZE							
ln AUW	0.85	0.71	0.82	0.85	0.76	0.53	0.84
ln EW	0.86	0.78	0.87	0.89	0.83	0.63	0.89
ln WTAREA	0.76	0.74	0.82	0.82	0.87	0.68	0.84
PERFORMANCE							
ln SPEED	0.86	0.71	0.59	0.82	0.58	0.77	0.76
ln SPCLS	0.78	0.68	0.51	0.74	0.56	0.73	0.70
ln SPPWR	0.80	0.69	0.56	0.73	0.55	0.78	0.72
ln ENERGY	0.87	0.68	0.57	0.80	0.53	0.72	0.75
ln CLIMB	0.63	0.52	0.43	0.52	0.36	0.62	0.54
ln SUSLD	0.38	0.33	0.28	0.28	0.28	0.47	0.34
ln THWT	0.61	0.57	0.46	0.51	0.43	0.68	0.57
ln BREG	0.70	0.60	0.43	0.66	0.71	0.67	0.64
ln USELD	0.46	0.26	0.41	0.37	0.23	0.31	0.38
ln PFFD	0.86	0.69	0.61	0.78	0.64	0.79	0.77
CONSTRUCTION							
ln ULTLD	0.36	0.27	0.32	0.30	0.24	0.44	0.32
ln STREFF	-0.20	-0.25	-0.13	-0.28	-0.33	-0.53	-0.25
ln CARRDV	-0.04	0.00	0.16	0.03	-0.14	-0.07	0.00
ln WGTYPE	0.58	0.72	0.46	0.62	0.64	0.81	0.64
ln WGWET	-0.37	-0.05	-0.17	-0.24	-0.11	-0.08	-0.21
ln EWAUW	-0.24	-0.05	-0.12	-0.07	0.04	0.25	-0.08
ln AVAUW	-0.01	0.24	0.19	0.12	0.20	0.15	0.16
ln BLBOX	0.85	0.74	0.81	0.85	0.76	0.60	0.85
PROGRAM							
ln TESTAC	0.19	0.37	0.01	0.16	0.43	0.56	0.23
ln TOOLCP	-0.54	-0.34	-0.53	-0.53	-0.30	-0.33	-0.49
ln ENGDV	0.11	0.01	0.02	-0.03	-0.05	0.09	0.03
ln EXPDV	-0.08	0.07	0.02	-0.04	0.11	-0.20	0.01
ln WSDV	0.81	0.79	0.75	0.81	0.78	0.71	0.83
ln PROGDV	-0.77	-0.77	-0.78	-0.81	-0.88	-0.78	-0.85

Table A.2

CORRELATION MATRIX FOR IDENTIFICATION OF PAIRWISE COLLINEARITY

	SIZE			TECHNICAL/PERFORMANCE									
	ln AUW	ln EW	ln WTAREA	ln SPEED	ln SPCLS	ln SPPWR	ln ENERGY	ln CLIMB	ln SUSLD	ln THWT	ln BREG	ln USELD	ln PFFD
SIZE													
ln AUW	1.00												
ln EW	0.97	1.00											
ln WTAREA	0.97	0.90	1.00										
TECH/PERF													
ln SPEED	0.87	0.88	0.49	1.00									
ln SPCLS	0.82	0.82	0.40	0.95	1.00								
ln SPPWR	0.43	0.40	0.43	0.93	0.87	1.00							
ln ENERGY	0.62	0.60	0.47	0.97	0.88	0.92	1.00						
ln CLIMB	0.27	0.31	0.28	0.81	0.79	0.93	0.76	1.00					
ln SUSLD	0.07	0.13	0.08	0.45	0.94	0.65	0.42	0.92	1.00				
ln THWT	0.21	0.31	0.29	0.72	0.65	0.92	0.69	0.92	0.77	1.00			
ln BREG	0.61	0.57	0.56	0.66	0.66	0.53	0.60	0.87	0.85	0.31	1.00		
ln USELD	0.77	0.77	0.70	0.50	0.40	0.40	0.46	0.34	-0.10	0.58	0.16	1.00	
ln PFFD	0.53	0.57	0.61	0.90	0.79	0.91	0.92	0.76	0.66	0.78	0.68	0.50	1.00
CONSTRUCTION													
ln ULTLD	0.12	0.13	-0.02	0.55	0.55	0.51	0.35	0.47	0.36	0.59	0.70	0.80	0.46
ln STREFF	0.03	-0.09	-0.02	-0.44	-0.46	-0.47	-0.30	-0.40	-0.80	-0.48	-0.81	-0.86	-0.94
ln CARRDY	0.00	0.06	0.17	-0.19	-0.31	-0.17	-0.06	-0.10	-0.20	-0.13	-0.33	0.28	-0.02
ln WGTYPE	0.34	0.42	0.41	0.57	0.51	0.58	0.40	0.41	0.40	0.49	0.74	0.12	0.62
ln WGWET	-0.40	-0.31	-0.21	-0.46	-0.47	-0.28	-0.44	-0.24	0.27	-0.03	-0.30	-0.78	-0.34
ln EWAUW	-0.43	-0.21	-0.12	-0.13	-0.16	0.09	-0.38	0.08	0.10	0.32	-0.31	-0.12	-0.02
ln AVAUW	-0.10	-0.04	0.17	-0.07	-0.13	-0.07	0.01	-0.14	-0.12	-0.06	-0.11	-0.03	-0.02
ln BLBOX	0.78	0.81	0.87	0.65	0.58	0.61	0.72	0.43	0.13	0.47	0.47	0.41	0.73
PROGRAM													
ln TESTAC	-0.09	-0.03	0.13	0.22	0.32	0.26	0.05	0.10	0.16	0.26	0.45	0.03	0.20
ln TOOLCP	-0.43	-0.44	-0.50	-0.48	-0.26	-0.43	-0.61	-0.06	-0.13	-0.31	-0.17	-0.00	-0.50
ln ENGDV	-0.14	-0.18	-0.34	0.13	-0.05	0.15	0.16	0.04	0.34	0.15	0.08	0.45	0.25
ln EXPDV	0.23	0.17	0.23	-0.39	-0.25	-0.51	-0.22	-0.61	-0.64	-0.57	-0.04	-0.19	-0.41
ln WSDV	0.67	0.66	0.74	0.72	0.76	0.63	0.67	0.40	0.30	0.42	0.69	0.23	0.70
ln PRGDV	-0.65	-0.71	-0.73	-0.73	-0.76	-0.67	-0.64	-0.63	-0.86	-0.49	-0.64	-0.32	-0.67

	CONSTRUCTION									PROGRAM				
	ln ULTLD	ln STREFF	ln CARRDY	ln WGTYPE	ln WGWET	ln EWAUW	ln AVAUW	ln BLBOX	ln TESTAC	ln TOOLCP	ln ENGDV	ln EXPDV	ln WSDV	ln PRGDV
CONSTRUCTION														
ln ULTLD	1.00													
ln STREFF	-0.63	1.00												
ln CARRDY	-0.10	0.30	1.00											
ln WGTYPE	0.27	-0.26	0.00	1.00										
ln WGWET	-0.38	0.18	0.16	0.13	1.00									
ln EWAUW	-0.02	-0.40	0.28	0.00	0.61	1.00								
ln AVAUW	-0.40	0.14	0.30	0.00	0.34	0.94	1.00							
ln BLBOX	0.02	-0.02	0.14	0.26	-0.28	-0.12	0.90	1.00						
PROGRAM														
ln TESTAC	0.20	-0.35	-0.34	0.40	0.15	0.26	0.10	0.04	1.00					
ln TOOLCP	-0.00	-0.07	-0.02	-0.16	0.30	0.11	-0.06	-0.02	0.13	1.00				
ln ENGDV	0.32	0.01	-0.00	0.10	0.02	-0.15	-0.01	-0.08	0.21	-0.80	1.00			
ln EXPDV	-0.57	0.36	-0.11	-0.23	0.00	-0.29	0.25	0.12	-0.03	0.35	-0.26	1.00		
ln WSDV	0.40	-0.30	-0.00	0.56	-0.06	-0.23	0.27	0.76	0.20	-0.31	-0.07	0.04	1.00	
ln PRGDV	-0.40	0.81	0.10	-0.53	0.87	-0.01	-0.23	-0.74	-0.33	0.31	0.70	0.04	-0.08	1.00

NOTE: Combinations above and to the right of heavy line were not considered because of the study assumption that an estimating relationship would not contain more than one variable from each class.

Appendix B

CALCULATED COSTS FOR ALTERNATIVE EQUATION SETS

Section XII of this draft summarized several alternative equation sets with respect to how closely, in percentage terms, they estimated the actual costs of the F-4, F-111, F-14, and F-15. This appendix contains a breakdown, by cost element, of these equation set estimates.

Table B.1

ESTIMATES OBTAINED FOR F-4 FROM REPRESENTATIVE EQUATION SETS ($M)

	Equation Set						
Cost Element	Actual	AUW/SPEED (Table 15)	AUW/SPPWR (Table 16)	AUW/CLIMB (Table 17)	AUW/PFFD (Table 18)	Single Best CER (Table 19)	Post-1960 Sample (Table 20)
Engineering	289	298	284	280	233	233	363
Tooling	209	218	214	205	196	223	194
Manufacturing labor	545	431	431	431	431	431	403
Manufacturing material	225	185	185	185	185	185	223
Development support	43	151	144	142	118	118	116
Flight test	95	50	49	42	41	51	103
Quality control	43	55	55	55	55	55	55
Sum of elements	1449	1388	1361	1340	1259	1297	1457
Total program CER	1449	1417	1535	1480	1274	1535	1514

Table B.2

ESTIMATES OBTAINED FOR F-111 FROM REPRESENTATIVE EQUATION SETS ($M)

	Equation Set						
Cost Element	Actual	AUW/SPEED (Table 15)	AUW/SPPWR (Table 16)	AUW/CLIMB (Table 17)	AUW/PFFD (Table 18)	Single Best CER (Table 19)	Post-1960 Sample (Table 20)
Engineering	632	625	516	414	530	530	650
Tooling	390	337	296	258	321	312	345
Manufacturing labor	588	715	715	715	715	715	628
Manufacturing material	441	356	356	356	356	356	369
Development support	360	317	262	210	269	269	208
Flight test	274	297	221	184	251	246	197
Quality control	97	91	91	91	91	91	86
Sum of elements	2782	2739	2457	2229	2532	2518	2482
Total program CER	2782	2710	2341	2515	2555	2342	2576

Table B.3

ESTIMATES OBTAINED FOR F-14 FROM REPRESENTATIVE EQUATION SETS ($M)

		Equation Set					
Cost Element	Actual	AUW/SPEED (Table 15)	AUW/SPPWR (Table 16)	AUW/CLIMB (Table 17)	AUW/PFFD (Table 18)	Single Best CER (Table 19)	Post-1960 Sample (Table 20)
Engineering	514	519	498	561	599	599	533
Tooling	228	302	295	307	336	292	283
Manufacturing labor	512	601	601	601	601	601	539
Manufacturing material	269	285	285	285	285	285	310
Development support	138	263	253	285	[illegible]	304	170
Flight test	132	158	149	170	199	149	149
Quality control	60	77	77	77	77	77	74
Sum of elements	1853	2204	2158	2286	2400	2307	2059
Total program CER	1853	2263	2203	2098	2601	2203	2148

Table B.4

ESTIMATES OBTAINED FOR F-15 FROM REPRESENTATIVE EQUATION SETS ($M)

	Equation Set						
Cost Element	Actual	AUW/SPEED (Table 15)	AUW/SPPWR (Table 16)	AUW/CLIMB (Table 17)	AUW/PFFD (Table 18)	Single Best CER (Table 19)	Post-1960 Sample (Table 20)
Engineering	445	335	415	356	493	493	370
Tooling	190	234	271	236	293	265	197
Manufacturing labor	430	437	437	437	437	437	408
Manufacturing material	201	189	189	189	189	189	226
Development support	161	170	211	181	250	250	118
Flight test	144	224	298	252	358	282	212
Quality control	80	56	56	56	56	56	56
Sum of elements	1651	1645	1876	1706	2076	1972	1587
Total program CER	1651	1534	1857	1503	2061	1857	1537

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